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Curing of High Performance Concrete: Annotated Bibliography

Building and Fire Research Laboratory
Gaithersburg, MD 20899

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By
Kenneth W. Meeks
and
Dr. Shahram Sarkani
Department of Civil, Mechanical, and Environmental Engineering
School of Engineering and Applied Science
The George Washington University
Washington, DC 20052

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ABSTRACT

This report consists of an annotated bibliography on the curing of high performance concrete (HPC). The scope of the bibliography is expanded somewhat beyond HPC to examine, in general terms, the current body of knowledge on the effects of various curing conditions on concrete. Also included in the bibliography are publications describing the basic physical and chemical effects of curing, since they will likely be the basis for further technological advancements in rational curing requirements for HPC. Many of the currently accepted concepts and theories related to the effects of curing on ordinary concrete and on the microstructure of cement paste are applicable to HPC. Since curing is closely related to water diffusion through concrete, the bibliography also addresses this topic. Finally, the bibliography includes references dealing with performance characteristics of structural concrete that are influenced by curing. This bibliography will assist those interested in reviewing some of the literature currently available related to curing concrete, in general, and to HPC specifically. It also reviews published articles and reports that address the urgent need for a coordinated research program to define optimum curing practices for the various types of HPC.

Keywords: Building technology; capillary pores; carbonation; compressive strength; cover; curing; durability; high performance concrete; high-strength concrete; maturity; permeability; porosity; portland cement; quality; research; shrinkage; silica fume

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1. INTRODUCTION

It has long been recognized that adequate curing is essential to obtain the desired structural and serviceability properties of concrete. Proper curing of concrete is one of the most important requirements for optimum performance in any environment or application. With respect to high performance concrete (HPC), the amount of information available on the effects of various curing conditions on its properties is limited. The curing of HPC has been identified as one of the critical areas in which more information and research are needed to realize the full potential of this relatively new class of concrete.

This annotated bibliography is the result of a recently completed literature search on the curing of HPC. This literature search will be used to write a state-of-the-art report on the curing of HPC. Included in the state-of-the-art report will be recommended research needs with respect to the curing of HPC. The scope of this bibliography is expanded somewhat beyond HPC to consider, in general terms, the effects of various curing conditions on concrete. The bibliography also includes literature addressing some of the basic physical and chemical aspects of curing. Many of the historically accepted concepts and theories of how curing alters the physico-chemical characteristics of cement paste are applicable to the study of HPC. A fundamental understanding of these physico-chemical properties of paste and how they are influenced by the curing process will be the foundation upon which further technological advancements can be made related to curing of HPC. Also included in this bibliography are references related to water diffusion through concrete since this is closely related to curing. There is also some information on the effect of curing on various performance characteristics of structural concrete, both conventional and high performance.

This annotated bibliography lists the references in chronological order in each chapter. The chapters cover the following periods:

- Chapter 2—Prior to 1970
- Chapter 3—From 1970 to 1990
- Chapter 4—From 1990 to 1995
- Chapter 5—From 1990 to 1996

A subject index is included to assist the reader in searching for references related to specific topics.

The summaries of each reference contain extracted information related either directly or indirectly to the curing of concrete. Particularly for the more recent literature, the emphasis is on the curing of HPC. Liberal use is made in the summaries of direct quotations from the references. This is the best way to convey most accurately the content of the article as well as the intent and purpose of the author(s).

In this publication, quantities have been expressed using SI units with the corresponding conversion to inch-pound units shown in parentheses. For continuity, this same procedure has also been used within the direct quotations. Where it was necessary to conform to this procedure within quotations, the appropriate units and conversions have been inserted by the authors of this bibliography.

This bibliography will assist those interested in reviewing some of the literature currently available related to curing concrete in general and to curing HPC specifically. Although good curing practices have been recognized for many years as being essential to quality concrete, the complexities of curing are still somewhat a mystery. Certainly further experimental and analytical research is warranted for developing curing methods and rational criteria most suited to HPC.

2. LITERATURE PRIOR TO 1970

2.1 **Bates, P. H., Author-Chairman, Committee 202, VARIATIONS IN STANDARD PORTLAND CEMENTS, Journal of the American Concrete Institute, Vol. 1, No. 1, November 1929, pp. 65-100.**

This is an early article which gives some interesting perspectives on curing issues being addressed in the 1920s. The author made the following statements:

- "The failure of obtaining results of strength determinations that could be reproduced from day to day has convinced everyone of the need of controlling particularly the humidity, and to a less degree the temperature of the atmosphere in which cement and concrete specimens are cured. But just how much either of these two necessities would affect different cements has not been a matter of much investigational concern. The committee therefore cannot cite much data that would show if curing conditions would indicate differences in cements."

- "There have been investigations studying the effect on strength of concrete cured at freezing or slightly higher temperatures, and at temperatures around that of boiling water or somewhat higher, through the use of autoclaves. But when the data are examined it will invariably be found that the cement has not been a variable."

- "The study of methods of curing and the effectiveness of the methods in reducing cracking and increasing strength and durability should be far more actively pursued than it is." This type of study "...is being done under the auspices of the National Research Council, insofar as road building is concerned. But the matter should be of just as much concern to all the other construction groups using cements."

2.2 **Gonnerman, H. F., STUDY OF METHODS OF CURING CONCRETE, Journal of the American Concrete Institute, Vol. 1, No. 4, February 1930, pp. 359-396.**

This is one of the earliest studies dealing with specifically the curing of concrete. The author summarizes the purpose of the study as follows:

"This laboratory investigation was undertaken in order to obtain information on the relative effectiveness of several of the methods advocated for curing concrete roads. Tests were made to study the effect of these methods on the compressive and flexural strength, wear and surface hardness of concrete, controlling as carefully as possible all the variables that might influence the results."

The article recognizes the importance of curing to the development of strength and resistance to wear. Investigations at this time had also shown that curing was essential for water-tightness and durability of concrete.

Water curing was recognized as the best curing method; however, there are instances where this method is not feasible, so other practices must be considered.

Some of the principal conclusions listed are as follows:

- "There were marked differences in the strength of similar specimens cured in the same manner but tested wet on the one hand and as cured--that is, dry or semi-dry on the other."

- "Cylinders cured by various methods showed only minor differences in compressive strength at ages of one to seven days, most of them having strengths equal to or greater than water-cured cylinders at these ages. At later ages, the differences in strength for the various methods became more marked and at 3 months and 1 year none gave strengths equal to continued water curings."

- "The results of the wear tests...emphasized the harmful effect of lack of curing or insufficient curing on the wearing resistance of the concrete."

When concrete is used in severe environmental conditions, subject to excessive wear, or experiences water pressure, curing is emphasized as being especially important.

2.3 **Gonnerman, H. F., CURRENT RESEARCHES ON PLAIN AND REINFORCED CONCRETE AND RELATED MATERIALS, Journal of the American Concrete Institute, Vol. 2, No. 5, January 1931, pp. 469-510.**

This report provides summaries of some of the research that was going on in the area of curing at this time.

The Kentucky State Highway Department and University of Kentucky, Lexington, were doing research on curing concrete pavements. The stated purpose of this work was "...to determine whether pavement protected with wet burlap for 24 hours is as satisfactory as that covered on the surface with calcium chloride following the 24-hour wet burlap curing." The results showed "...there is no advantage in using calcium chloride, since almost equal strengths were obtained for both treated and untreated concrete, and the untreated concrete developed sufficient strength at 7 days both in flexure and compression to permit opening the pavement." The intent of the calcium chloride was to keep the surface of the concrete wet due to its deliquescent property (absorbs water from the air).

The Wisconsin Highway Commission, Madison, was doing research to compare methods of curing concrete pavements. Wet earth curing was the basis of comparison.

The Missouri State Highway Department, Jefferson City, was doing research on the loss of moisture from concrete cured by various methods. The purpose of these tests was to determine the relative efficiency of various curing methods in keeping concrete moist during the curing period.

The Pennsylvania Department of Highways, Harrisburg, was doing research on the effect of different methods of curing on strength of concrete. This research involved an evaluation and comparison of the value of wet straw, calcium chloride used integrally, and asphaltic emulsion sprayed on the surface as curing agents.

The Iowa State Highway Commission, Ames, was doing research on methods of curing concrete. This project was concerned particularly with curing of concrete pavement slabs. The results reported were "...that the wet burlap moist earth method of curing is the most efficient method available; that other methods afford strength results of varying percentages of the results obtained for this method; that asphaltic coatings...are 90 to 95% as effective as this method; that calcium chloride on the surface is about the same; and that the original water content of the concrete must be maintained or even augmented for the most efficient curing."

2.4 **Timms, A. G. and Withey, N. H., TEMPERATURE EFFECTS ON COMPRESSIVE STRENGTH OF CONCRETE, Journal of the American Concrete Institute, Vol. 5, No. 3, January-February 1934, pp. 159-180.**

This paper reported on tests initiated primarily to determine the effects on concrete strength of exposure to winter temperatures. The investigation involved both normal and high-early strength cements in use at that time.

The value of moist curing was evident as it gave the highest strengths at all ages after 7 days for the high early strength cements, and after 3 days for the normal cement. Six different curing conditions were used with ages at testing ranging from 1 day to 3 months. The first curing method was standard moist-room curing in which the specimens were removed from molds after 1 day, then stored in the moist room until tested. The second curing method was storage in a moist room for 2 days after removal from mold after 1 day, then curing in the laboratory air until testing. The other four curing methods consisted of curing in the molds for 1, 3, 7, and 28 days, then air storage at 21 °C (70 °F) until tested. There was some reduction in strength at the 3 month period due to drying for those specimens removed from molds and cured in air with a 50% relative humidity.

There were four significant conclusions listed as follows:

- "The rate of hardening of the concrete following a given initial treatment was dependent on the temperature of exposure. The 28-day strengths obtained with storage temperatures of 10 and 0.5 °C (50 and 33 °F) were, in general, from 50 to 75% of those obtained with concrete moist cured at 21 °C (70 °F). The rate of gain in strength with age was less for concrete exposed to 0.5 °C (33 °F) than to 10 °C (50 °F). Even at -9 °C (16 °F) the richest mix concrete showed a definite gain in strength."

- "Subsequent warming of concrete exposed to temperatures of 10 and 0.5 °C (50 and 33 °F) was not of much benefit in improving the later strengths when no provision was made to supply moisture to further the curing action. The greatest benefit from warming occurred with the concrete exposed to -9 °C (16 °F)."

- "The importance of the duration of the period of initial curing is brought out in a striking manner by the tests. The indications are that when the temperature of exposure is from 0.5 to 10 °C (33 to 50 °F), the initial curing period at 21 °C (70 °F) should be at least 3 days for normal cement and at least 1 day for high early strength cement. When the temperature of exposure is below freezing, these minimum initial curing periods should be increased depending on the strength required for safety. For concretes exposed to temperatures below freezing, the strength at any time after the period of initial curing depends primarily on the strength developed during the initial curing period."

- "Comparisons of the strengths of concrete made at different temperatures show the danger of placing concrete having a temperature less than 21 °C (70 °F) where it is to be exposed to temperatures below freezing."

2.5 **Timms, A. G. and Withey, N. H., FURTHER STUDIES OF TEMPERATURE EFFECTS ON COMPRESSIVE STRENGTH OF CONCRETE, Journal of the American Concrete Institute, Vol. 6, No. 2, November-December 1934, pp. 165-180.**

This article supplements the previous one by these same two authors. It reports on additional tests and studies related to temperature effects. This paper considers the effect of subsequent moist curing in developing the potential strength of the concrete. In the studies reported in the previous article, the concrete, upon removal from the cold rooms, was stored in air at 21 ± 3.3 °C (70 ± 6 °F) and at about 50% relative humidity and no moisture was furnished for further curing.

When specimens were stored in water subsequent to exposure to low temperatures, the rate of gain in strength was approximately the same regardless of the duration of exposure.

It was noted that concrete can be chilled for a long period and still develop its required strength when treated with warm water, provided no ice crystals are formed.

The following conclusions are listed by the authors:

- "Where the development of normal strength of concrete has been retarded by exposures to low temperatures, the concrete can be brought to practically full potential strength by saturation with warm water for a sufficient period. While in these tests heating alone with air at 50% relative humidity did give some increase in strength, it was only in the presence of an adequate supply of moisture that the potential strength of the concrete was attained. Even such short periods in water as 3 days at 22 °C (72 °F) were of great value in increasing strength."

- "In these tests there was no evidence of the formation of ice crystals, even when exposed to the low temperature after 6 hours at 27 °C (80 °F)."

- "Concrete exposed in water at a given low temperature had a much higher proportion of its potential strength than did concrete exposed for the same period and at the same temperature in dry air."

- "Preliminary curing in air at 27 °C (80 °F) for ¼, 1, or 3 days before immersion in water at 22 °C (72 °F) gave greater concrete strengths in all cases than when immersed immediately in the water."

- "For concrete made with normal cement and stored in water at either 10 or 0.5 °C (50 or 33 °F), the strength at any age increased as the length of preliminary air storage at 27 °C (80 °F) was increased from 0 to 3 days. For concrete made with high-early strength cement, the strength increased as the preliminary storage was increased from 0 to 1 day, but 3 days preliminary storage was of little or no additional benefit."

- "The higher strengths obtained with preliminary curing at 27 °C (80 °F) as compared with concrete made and placed at 10 °C (50 °F) for all conditions of exposure indicate the desirability of placing concrete at normal temperatures wherever possible."

2.6 **Edwards, Harlan H., Author-Chairman of Committee 107, PROPERTIES OF JOB-CURED CONCRETE AT EARLY AGES, Journal of the American Concrete Institute, Vol. 8, No. 1, September-October 1936, pp. 41-64.**

This article describes some of the concerns related to job site curing and concrete quality during the mid-1930s.

The author stresses the importance of being aware of the curing temperature. It was understood that, except for certain variations in the region above 21 °C (70 °F), concrete hardens more rapidly as the temperature increases, and also that concrete cured at low temperatures, above the freezing point, gains strength more slowly.

The author closes with the following summary statements which he says may need corroboration by further testing:

- "Under careful control, concrete in the structure can be generally of higher strength and of greater density than that indicated by test cylinders laboratory-cured. Due to the lack of adequate curing, together with rule-of-thumb design and careless placing methods, however, concrete in the ordinary job should normally be expected to have somewhat lower comparative characteristics."

- "Concrete in monolithically-finished slabs is of higher strength and greater density than the same concrete placed in walls."

- "Concrete in walls and columns has its greatest strength and density at the lower part of the section placed at one time, decreasing toward the top of the section due to water-gain."

- "Longer curing than the usual 3 to 7-day period, coupled with properly designed, leaner concrete, tends to produce a more economical job, of equal job strength to wetter concrete of the same water-cement ratio, yet having lower shrinkage and expansion characteristics."

- "Test cylinders, job cured, are not usually representative of the concrete in the structure, due to unavoidable differences in moisture and temperature curing conditions as well as in the water-cement ratio at time of set."

- "In all strength tests of portland cement, temperature at the time of test should be closely controlled, since results are of value only when they can be compared with standards. Test temperatures higher than 21 °C (70 °F) decrease the strength materially, while lower temperatures increase the strength to a smaller degree."

- "Adequate curing requires the continued presence of moisture supplies by repeated wetting of all parts of the structure, the necessary frequency of which is dependent upon the air temperature and upon the character of the constituents of the cement used."

- "Concrete controlled by cores cut from the finished structure is now economically possible and advisable due to recent perfection and simplification of portable core-cutting equipment."

2.7 **CONCRETE CURING METHODS, ASTM STANDARDS, Journal of the American Concrete Institute, Vol. 16, No. 4, February 1945, pp. 349-355.**

ASTM, in deference to ACI activity in the realm of field practice, withdrew its standards for curing portland cement concrete. In this article, ACI published the latest ASTM standards on concrete curing as interim information pending the completion of the work of ACI Committee 612, Recommended Practice for Curing Concrete.

Standard Method of Curing Portland-Cement Concrete Slabs with Wet Coverings

Burlap coverings: After the final finishing operation the concrete shall be covered for not less than 18 hr. by a double thickness of burlap kept saturated with water.

Protection of surface: Immediately after the removal of the burlap, the surface of the slab shall be protected by one of the following methods: Ponding; wet earth, sand, or sawdust; or wet straw or hay.

Standard Specifications for Curing Portland-Cement Concrete

These specifications cover the curing of concrete for all purposes including necessary precautions during the curing period in cold weather.

The concrete shall be so cured that the compressive or flexural strengths of specimens of the concrete 28 days old are not less than 90% of the strengths of 28-day-old specimens of the same concrete cured in moist air at a constant temperature of 21 °C (70 °F). Either compression or flexure should be selected according to whether the concrete is designed for compression or bending stresses.

Curing during cold weather: Protected concrete when deposited shall have a temperature of not less than 10 °C (50 °F) nor more then 38 °C (100 °F). The freshly-deposited concrete and the surrounding air shall be maintained at a temperature of not less than 10 °C (50 °F) nor more than 38 °C (100 °F), until the concrete has attained 80% of the strength for which the concrete was designed. Exposed concrete for which the surrounding air cannot be artificially heated shall not be placed when the air temperature is lower than 4.5 °C (40 °F). The concrete when deposited shall have a temperature of not less than 10 °C (50 °F) nor more then 38 °C (100 °F).

2.8 RECOMMENDED PRACTICE FOR MEASURING, MIXING AND PLACING CONCRETE (ACI 614-42), Journal of the American Concrete Institute, Vol. 16, No. 6, June 1945, pp. 625-649.

This was a report by Committee 614 in response to an expressed need for an outline of good concrete practices including the placing of the finished product. Their recommendations were presented as an ACI Standard, not as a specification. The Committee also termed their recommendations as "best practices" or "best methods".

There was some mention of curing in this report, although it did not specifically deal with curing requirements.

The Committee did not provide any general curing criteria; however, they did discuss cold weather and hot weather concreting. The report says: "In connection with cold weather protection, such precautions should be taken that the curing of the concrete will not be impaired and that no portions of the work will become overheated. It is important that there should be a curing period of sufficient length at temperatures above freezing so that when it is exposed to temperatures below freezing at the end of the curing period the concrete will not be injured."

Another portion of the article states: "With adequate protection of the surfaces from freezing, the minimum temperature of freshly mixed mass concrete may be permitted to be as low as 4.5 °C (40 °F) when placed, because the heat of hydration is lost much more slowly from this type of concrete."

With respect to hot weather concreting, "For best ultimate quality, concrete should be placed at the lowest practicable temperature during hot weather. [...] Curing should preferably be obtained by sprinkling or covering with moist burlap for its additional cooling value. If curing must be done by means of black bituminous sealing compounds, they should be given a coat of whitewash promptly so as not to expose the heat absorbing black surface to the sun."

NOTE: Articles 2.9 through 2.18 are from: **STUDIES OF THE PHYSICAL PROPERTIES OF HARDENED PORTLAND CEMENT PASTE, by T. C. Powers and T. L. Brownyard,** published in the Journal of the American Concrete Institute. These provide classical information on the structure of cement paste

2.9 SYNOPSIS, Journal of the American Concrete Institute, Vol. 18, No. 2, October 1946, pp. 101-105.

These studies deal mainly with data on water fixation in hardened portland cement paste, the properties of evaporable water, the density of the solid substance, and the porosity of the paste as a whole. The discussions include several topics of direct interest to the curing requirements of concrete, including capillary-flow and moisture diffusion, and permeability and absorptivity. These articles were directed primarily toward all who were engaged in research on portland cement and concrete.

2.10 PART 1. A REVIEW OF METHODS THAT HAVE BEEN USED FOR STUDYING THE PHYSICAL PROPERTIES OF HARDENED PORTLAND CEMENT, Journal of the American Concrete Institute, Vol. 18, No. 2, October 1946, pp. 105-132.

A program of studies of the properties of the hardened paste was begun in the Portland Cement Association Research Laboratory in 1934. These studies dealt primarily with the fixation of water, but also involved measurements of the heat-effects accompanying the regain of water by the previously dried paste, measurements of the freezing of the water in the saturated paste, and many other matters related to cement paste.

In 1941 "...Eitel concluded that although the hydration products of portland cement are predominantly colloidal, they appear crystalline—not amorphous—to the electron microscope." The majority of crystals found by investigators have been in the colloidal size range.

Bogue and Lerch (1934) are credited with the use of X-ray analysis in connection with microscopic examination. The X-ray analysis "...confirms the microscopic indication that unaltered beta or gamma dicalcium silicate remained in pastes after 2 years of curing."

The following information is extracted from the summary of Part 1:

- "The material presented in Part 1 attempts to review the most significant information obtained by other investigators on the physical properties of hardened portland cement paste."

- "From reported microscopic studies it can be concluded that hardened cement paste is predominantly of submicroscopic texture."

- "The relatively few reported observations made with the electron microscope indicate that the hydration products of portland cement may be colloidal but not amorphous. That is, they may be made up of submicroscopic crystals."

- "Any solid is capable of holding a small amount of water or other substance on its exposed surface by adsorption. The quantity held in this manner can be large when the specific surface of the solid is very high."

- Indications are that "...water in hardened paste is not held as it is in microcrystalline compounds. Instead, the manner of binding is similar to that between water and silica gel."

2.11 PART 2. STUDIES OF WATER FIXATION, Journal of the American Concrete Institute, Vol. 18, No. 3, November 1946, pp. 249-336.

In this paper, the results of studies of water fixation conducted in the laboratory are reported.

The authors introduce the subject of water fixation and its importance as follows:

"Some of the water associated with hardened cement paste is obviously a constituent of the new solids produced by chemical reactions. If all such water is driven from the paste, the cohesion of the paste is destroyed. Another part of the water, amounting in saturated paste to as much as 50% of the volume of the paste, or even more, is free to leave the hardened paste without destroying the cementing value of the material. It does, however, have important effects on the hardened paste: the paste shrinks as water is lost and swells as it is gained; the strength and hardness of the hardened paste vary with its degree of saturation; some of this water is freezable and is thus a source of disruptive pressures that tend to disintegrate concrete exposed to weather. Furthermore, the amount of water that is free to come and go in response to changes in ambient conditions is an index to the degree of porosity of the hardened paste. The porosity is obviously an important property of the material related directly to its quality."

The reason for adsorption is explained as follows: "Regardless of the size of the pore, a substance near enough to the boundary of the pore is attracted toward the boundary by one or more types of force known collectively as forces of adsorption. These forces are sufficiently intense to compress a fluid that comes within their range."

Porous bodies of submicroscopic (colloidal) texture shrink and swell noticeably as they experience variations in the liquid content of the pores, the magnitude of the effect being primarily influenced by the strength of attraction between the solid and the liquid.

This part of the overall studies "...aims to elucidate those features of a hardened paste that are revealed by the relative proportions of the total water content that fall in three different categories, as follows:

1. Water of constitution: As used here, this term refers to water of crystallization or water otherwise chemically combined; it refers to water that is a part of the solid matter in a hardened paste.
2. Water bound by surface-forces—adsorbed water
3. Capillary water"

Microscopic evaluation shows that both microcrystalline and colloidal materials occur in hardened cement paste. The colloidal material is evident as an amorphous mass which encircles microcrystalline and unhydrated residues of the original cement grains.

The water content of a colloidal hydrate is changing all the time as ambient conditions vary.

The water that a specimen is able to hold in addition to the non-evaporable water is commonly referred to as the evaporable water.

The nature of cement paste is such that a specimen can remain saturated only under two conditions—when it comes into contact with saturated water vapor or with liquid water.

In relation to the study of evaporable water, the article provides these definitions: "The taking up of moisture from the atmosphere will be referred to as adsorption, and the reverse will be called desorption, even though other processes might be involved. [...] When speaking of both processes collectively or of the processes in general without specifying the direction of moisture change, the term sorption will be used."

Regarding the curing period of a cement paste, the following points are noted:

- "The total water held at saturation...increases as the length of the curing period increases."
- "The non-evaporable water content also increases."
- "The amount of water held at any intermediate vapor pressure increases with the length of the curing period."
- "The evaporable water content, which is the difference between the total and the non-evaporable water, decreases as the length of the curing period increases."

With respect to hydration, when the length of time of moist curing increases, the total evaporable water decreases and the amount held at low vapor pressures increases. Also, it is noted that: "Since the total evaporable water may be taken as a measure of the total porosity of the hardened paste,...the amount of water held at vapor pressures near the saturation pressure depends on the porosity of the sample."

Data from laboratory studies reported in this article show that "...with any given cement the adsorption at low vapor pressure (any pressure below about 0.4 p_s) is directly proportional to the extent of hydration as measured by the non-evaporable water content." [p_s = pressure of saturated vapor]

The following information is extracted from the summary of this article:

- "The water in saturated hardened cement is classified as evaporable and non-evaporable. [...] The pores in a hardened paste are defined as those spaces occupied by evaporable water."
- "Adsorption and desorption curves from the same sample present a so-called hysteresis loop similar to those found for other materials. In addition, the curves show some features of irreversibility not commonly found among other materials."
- "For a given cement the amount of evaporable water held at any pressure up to about 0.4 p_s is directly proportional to the non-evaporable water content. The proportionality constant is different for cements of different type."

- "Results show that curing at high temperature and pressure produces adsorption characteristics radically different from those observed in specimens cured in the ordinary way."

2.12 PART 3. THEORETICAL INTERPRETATION OF ADSORPTION DATA, Journal of the American Concrete Institute, Vol. 18, No. 4, December 1946, pp. 469-504.

Different theories have been advocated in the past to explain the taking up of gases and vapors by solid materials. Perhaps the most useful is the theory of Brunauer, Emmett, and Teller, commonly called the multimolecular-adsorption theory, or the B.E.T. theory, as it is frequently abbreviated.

The taking up of a gas by a solid is believed to be caused by the physical attraction that occurs between the molecules of the gas and the surface molecules of the solid.

According to the B.E.T. theory, at any given vapor pressure, the amount adsorbed is directly proportional to the surface area of the solid.

The basis of the capillary-condensation theory used in the study of cement paste is the realization that the surface of a liquid is the seat of available energy.

This conclusion is stated: "When adsorption of a vapor occurs in a porous solid of granular or fibrous structure, the liquid surfaces are certain not to be plane. They will be concave, at least in some regions. Therefore, the free surface energy of the solid and the free surface energy of the condensed liquid must both be causes of condensation."

In the analysis of cement paste, "...the pores are considered to be the spaces vacated by evaporable water when the sample is dried. The drying may be accompanied by irreversible shrinkage so that the dried sample may not faithfully represent the original paste."

For specimens of sufficiently low water-cement ratio, it has been determined that curing is capable of eliminating all capillary water.

The following points are extracted from the summary of the article:

- "The evaporable-water capacity is smaller the lower the original water-cement ratio and the longer the period of curing, but it cannot be reduced below about $4V_m$." [V_m = quantity of water required for a complete condensed layer on the solid, the layer being 1 molecule deep]

- "Evaporable water in excess of $4V_m$ is believed to occupy interstitial space not filled by gel or other hydration products. The water in this space is called capillary water. The rest of the evaporable water is held within the characteristic voids of the gel and is called gel-water even though some of it might have been taken up by capillary condensation."

- "When the total evaporable-water capacity = $4V_m$, the specimen contains no space for capillary water."

2.13 **PART 4. THE THERMODYNAMICS OF ADSORPTION OF WATER ON HARDENED PASTE, Journal of the American Concrete Institute, Vol. 18, No. 5, January 1947, pp. 549-602.**

This portion of the studies relates to the energy changes that occur when water is adsorbed by hardened cement paste.

Test results show the heat of hydration is directly proportional to the non-evaporable water content of a cement paste.

The heat of hydration may be depicted as developing in the following way:

1. "Chemical reactions between the cement and water in the fresh paste produce new solid phases in which the non-evaporable water is an integral part. These reactions release a definite amount of heat for each unit of water combined, but the amount is different for cements of different chemical composition."

2. "As the new solid phases (the reaction products) form, they adsorb water and the heat of adsorption is released."

3. "The total heat of hydration is the sum of the heat of combination of the non-evaporable water and the net heat of adsorption...."

The total net heat of adsorption of the evaporable water in a given paste has been found to be about $\frac{1}{4}$ of the total heat of hydration.

Concerning adsorption, the authors state: "It seems reasonable to regard the net heat of adsorption as representing the result of changes in the internal structure of the water (changes in the association and orientation of the molecules) and in the potential energy of the water molecules caused by the mutual attraction between the water molecules and the surface. The surface of the solid probably remains structurally unchanged."

Adsorption will occur in a cement paste when "...the free energy of the free water or free vapor is greater than the free energy of the adsorbed or capillary condensed water."

Swelling within the gel is described as follows: "When some kinds of gel are placed in contact with a suitable liquid, they imbibe liquid and swell until they have become molecular or colloidal solutions. This is called unlimited swelling. The same gels with another type of liquid may imbibe only a limited amount and show correspondingly limited swelling."

The specific characteristics of portland cement gel are described as follows: "Portland cement gel in water belongs to the limited-swelling class. Like other gels of its class, it is not able to swell beyond the dimensions established at the time of formation. However, it will shrink on loss of evaporable water and swell when evaporable water is regained." Cement gel undergoes a permanent shrinkage on first drying, so that only a portion of the initial shrinkage is capable of being reversed.

With regard to the volumetric behavior of cement paste and concrete, the authors state: "The gel in the paste is not composed of discrete particles but is apparently a coherent, porous mass held together by solid-to-solid bonds. Moreover, it contains microcrystals and aggregate particles that resist the shrinkage of the gel. Consequently, swelling (or shrinkage) in concrete is partially opposed by elastic forces developed throughout the mass...."

From the study of shrinkage and swelling characteristics, "...it would appear that the over-all volume change of the paste should be proportional to the change in spacing of the solid bodies that are held apart by adsorbed water. This spacing should decrease as adsorbed water is withdrawn and increase as adsorbed water is added."

The shrinkage and swelling that occur in rigid porous bodies that experience volume changes much smaller than the corresponding changes in water content can be thought of as capillary phenomena.

Also stated in relation to volume changes: "When concrete undergoes shrinkage for the first time, it is unable to regain its original dimensions when it becomes resaturated. This can be accounted for in terms of the capillary theory by assuming that the stresses of shrinkage cause plastic flow in the solid phase. Hence, the permanent shrinkage, that is, the irreversible part of the initial shrinkage, can be regarded as permanent set."

On the subject of free energy, the authors state: "...inequalities in stress and strain produce inequalities in the free energies of both the adsorbed water and capillary water and thereby induce redistributions of moisture within the mass. This...is an important factor in the gradual yielding of concrete under sustained stress known as creep or plastic flow. The changes in moisture distribution cause localized shrinkings and swellings with consequent changes in the deformation of the body as a whole."

When temperature gradients are present in a concrete mass, water will migrate in the direction of descending temperatures.

Other effects due to movement are mentioned: "...movement of water...is accompanied by shrinkage in the regions where the temperature is increased which tends to offset the expansion due to swelling and thermal expansion. Conversely, in the regions where the temperature is lowered, swelling tends to offset the shrinkage and thermal contraction."

It seems clear "...that deformations of the solid phase and temperature changes together or separately cause moisture movements in concrete." When concrete is "...subjected to changing external forces or temperature or both, the evaporable water must be in a continual state of flux. If the ambient humidity also fluctuates, the internal moisture movements are still further complicated. Possibly these effects have an influence on the ability of concrete to withstand weathering."

Pertinent information from the summary of this article include the following:

- "The total net heat of adsorption of hardened paste is approximately equal to the heat of immersion of the adsorbent."

- "Among portland cements of all types the total heat of hydration ranges from about 485 to 550 cal per g of non-evaporable water." Tests "...indicate that of this amount about three-fourths is due to the heat of reaction of the non-evaporable water and the rest is due to the net heat of adsorption of the evaporable water."

- "Cement gel belongs to the limited swelling class of gels."

- "The order of magnitude of the total volume change of hardened cement paste can be accounted for on the assumption that the change is due to the removal or addition of the first layer of adsorbed water molecules."

- Tests show "...volume change is directly proportional to a part of the total change in water content." Research data has shown "...that volume change is independent of the change in capillary-water content." Data from this paper "...suggest that volume change may be proportional to the change in gel-water content, rather than to the change in the first layer only."

- "Changes in external forces and changes in ambient temperature and humidity keep the evaporable water of a partially saturated specimen in a continual state of flux. This possibly influences durability."

2.14 PART 5. STUDIES OF THE HARDENED PASTE BY MEANS OF SPECIFIC-VOLUME MEASUREMENTS, Journal of the American Concrete Institute, Vol. 18, No. 6, February 1947, pp. 669-712.

The importance of non-evaporable water is described: "The non-evaporable water is regarded as an integral part of the solid phase in hardened cement paste. In becoming a part of the solid material some or all of it may have lost its identity as water. Nevertheless, the absolute volume of the solid phase can be considered as being equal to the original volume of the cement plus the volume of the non-evaporable water."

About capillary water, the authors state: "...any capillary water present will either be in a state of tension or under no stress at all. If the specimen is not saturated, so that the vapor pressure of the contained water is less than p_s but more than about 0.45 p_s, capillary water will be present and under tension. [...] If the paste is saturated, so that $p = p_s$, the capillary water will be under no tension."

The total water content of a cement paste is comprised of two components. One component is the free water, and the other one is the water having a mean specific volume less than 1.0.

An important experimental finding is "...that the non-evaporable water cannot become more than about one-half the total water content of a saturated paste."

Concerning the specific volume of the non-evaporable water, it "...may have no literal significance, since at least a part of the non-evaporable water probably loses its identity when it enters into chemical combination with the cement constituents."

Tests show "...that during the first month or so the average rate of hydration of a given cement is greater the greater the original water-cement ratio. After the first 3 months the rate is very slow." Results also show that "...even with the slow hardening cements, hydration virtually ceases within a year."

The authors list the following important results from their work:

- "Pastes in which the original cement constitutes more than 45 percent of the over-all volume cannot become hydrated to the same extent as pastes containing less cement. In terms of weight ratio, this means that if w_o/c is less than 0.40, ultimate hydration will be restricted." [w_o/c = original water-cement ratio]

- "The average rate of hydration is lower the lower w_o/c. Therefore, the age-strength relationship for ordinary concrete cannot be the same as that for standard test pieces of low w_o/c."

- "The substance that gives concrete its strength and hardness is the solid material formed by the hydration of portland cement."

- "The hydraulic radius of the pores in the paste and the porosity are smaller the smaller the proportion of capillary space in the hardened paste."

- "The permeability of hardened pastes to fluids under external pressure probably depends almost entirely on the proportion of capillary water, owing to the extreme smallness of the gel-pores."

The closing of this article contains this summary statement concerning a saturated specimen:

"The total water in a saturated specimen can be divided into two categories: (a) that which has a specific volume less than 1.0; (b) that which has a specific volume equal to 1.0. All the water having a specific volume less than unity is called compressed water. It comprises the non-evaporable water and a part of the evaporable water."

2.15 **PART 6. RELATION OF PHYSICAL CHARACTERISTICS OF THE PASTE TO COMPRESSIVE STRENGTH, Journal of the American Concrete Institute, Vol. 18, No. 7, March 1947, pp. 845-865.**

Concerning strength gain in the cement paste, the authors state: "We may tentatively assume that the increase in strength that accompanies an increase in extent of hydration is a function of the increase in the volume of the solid phase per unit of volume of initially water-filled space."

All indications are that the increase in strength of the paste is directly proportional to the increase in V_m/w_o and is independent of age, original water-cement ratio, or identity of cement.

The strength of hardened paste is influenced by its chemical constitution as well as its gel-space ratio.

With respect to steam curing, it was shown "...that the relation of f_c' to V_m/w_o found for specimens cured at one temperature and pressure will not hold at another widely different temperature and pressure."

Test "...data indicate that among specimens cured at different temperatures ranging from 21 to 177 °C (70 to 350 °F), the properties of the specimens show no differences that are disproportionate to the difference in curing temperature." It is concluded "...that the f_c'-vs.-V_m/w_o relationship must change progressively as the temperature of curing is increased above normal. Presumably, it would change also if the temperature were lowered."

"Werner and Giertz-Hedstrom [in 1931] found that strength could be expressed as a function of the volume of solid phase per unit volume of hardened paste. The solid phase was defined as the volume of the original cement plus the water that is not evaporable in the presence of concentrated H_2SO_4."

Giertz-Hedstrom concluded in 1938 that, as an approximation, strength could be considered to be a function of the degree of hydration and independent of the kind of cement.

"Any attempt to express the strength of concrete or mortar as a function of only one independent variable is certain to meet with but limited success at best, for the reason that more than one independent variable is involved."

The air content of the paste has some impact on the strength developed, the higher the air content the lower the strength, other factors being equal.

On the effect of aggregates, the authors state "...although pertinent data are lacking, we may surmise that the strengths of adhesion between the hardened paste and the aggregate differ among concretes made with aggregates of different mineral composition. This will account for differences in strength, especially tensile strength."

"When cements of ordinary C_3A content are compared, the findings show that the strength at a given V_m/w_o is highest for the low-C_3A cements. It should be noted that this observation does not pertain to the rate of hydration or the rate of strength development. Cements high in C_3A usually hydrate more rapidly and develop higher early strengths than those low in C_3A." This "...means that when two pastes of the same original water-cement ratio reach the same degree of hydration, as indicated by their gel-space ratios, the cement having the lower C_3A content will probably have the higher strength."

2.16 PART 7. PERMEABILITY AND ABSORPTIVITY, Journal of the American Concrete Institute, Vol. 18, No. 7, March 1947, pp. 865-880.

"For cement pastes, the total porosity, ε, may be taken as being equal to the volume of the total evaporable water."

It is reasonable to assume that well cured, neat paste of low water-cement ratio is practically impermeable.

"Introduction of aggregate particles into paste tends to reduce the permeability by reducing the number of channels per unit gross cross-section and by lengthening the path of flow per unit linear distance in the general direction of flow. However, during the plastic period, the paste settles more than the aggregate and thus fissures under the aggregate particles develop. In saturated concrete these fissures are paths of low resistance to hydraulic flow and thus increase the permeability of the concrete. In general, with paste of a given composition and with graded aggregate the permeability is greater the larger the maximum size of the aggregate."

The authors also state: "...for well cured concretes having water-cement ratios above about 0.5, the permeability is determined largely by the by-passes around the gel and the by-passes around the paste in the concrete structure as a whole."

The term "absorptivity" can be considered to be the characteristic rate at which dry or partially dry paste absorbs water in the absence of any type of external hydraulic pressure.

"For pastes containing capillary space outside the gel, it is believed that the water is taken in by two different processes. The water enters the capillary system under the influence of capillary force, i.e., surface tension. Probably most of the water entering the gel, if not all, is drawn by adsorption forces."

The summary from this article states the following:

- "The permeability of concrete is generally much higher than the theoretical permeability owing to fissures under the aggregate that permit the flow partially to by-pass the paste and owing to the capillaries in the paste that permit the flow in the paste to by-pass the gel."

- From the study of absorptivity, indications are "...that the initial absorption takes place almost exclusively in the capillaries outside the gel, when such capillaries are present."

2.17 PART 8. THE FREEZING OF WATER IN HARDENED PORTLAND CEMENT PASTE, Journal of the American Concrete Institute, Vol. 18, No. 8, April 1947, pp. 933-969.

This part, of the overall studies reported in this series of articles, contains data on the amount of ice that can exist in hardened portland cement paste under given conditions.

"From the fact that the evaporable water in hardened paste exhibits different vapor pressures when the sample is at different degrees of saturation, we could anticipate the known fact that not all evaporable water in a saturated paste can freeze or melt at a fixed temperature."

"It is clear...that the evaporable water in a saturated hardened paste will not begin to freeze at 0 °C (32 °F) because of its content of dissolved hydroxides. Moreover, when freezing begins, and pure ice separates from the solution, the solution becomes more concentrated and thus the freezing point is lowered further. It follows that the evaporable water will freeze progressively as the temperature is lowered."

"The maximum amount of water in a saturated paste that may be frozen at a given temperature may be estimated from the non-evaporable and total water contents."

"As would be expected, the final melting point, that is, the highest temperature at which ice can exist in a specimen of hardened paste, is lower the lower the degree of saturation of the specimen."

The summary of this article contains the following information:

- "The final melting point in a saturated paste (temperature at which the last increment of ice disappears) ranged from -0.05 to -1.6 °C (31.9 to 29.1 °F). The temperature seemed to depend on the alkali content of the cement, the higher the alkali content, the lower the final melting point."

- "The ice is believed to form in the capillary space outside the gel. It is unlikely that the gel water freezes in place, although, at low temperatures, it contributes to the ice."

- "When a paste is not fully saturated, the final melting point is lower than that for the same paste when saturated." The maximum amount of freezable water in a paste at a given degree of saturation can be estimated fairly accurately from the 25 °C (77 °F) sorption isotherm and the phase equilibrium diagram for water and ice.

2.18 PART 9. GENERAL SUMMARY OF FINDINGS ON THE PROPERTIES OF HARDENED PORTLAND CEMENT PASTE, Journal of the American Concrete Institute, Vol. 18, No. 8, April 1947, pp. 971-992.

In this article, the final part of this series of papers, the concepts concerning the characteristics of hardened paste that have emerged from this study are summarized. All the data and relationships discussed in this summary article are applicable only to specimens cured continuously at about 21 °C (70 ° F).

"The hardened paste is considered to be not a continuous, homogeneous solid, but rather to be composed of a large number of primary units bound together to form a porous structure." The studies being reported indicate "...that many significant characteristics are dependent not primarily on chemical constitution but rather on the physical state of the solid phase of the paste and its inherent attraction for water."

"The extreme smallness of the structural units of the paste, the smallness of the interstitial spaces, and the strong attraction of the solid units for water account for the fact that changes in ambient conditions are always accompanied by changes in the moisture content of the hardened paste; moreover, these factors account for the changes in volume, strength, and hardness that accompany changes in moisture content."

The pores in hardened portland cement paste are usually defined as the space in the paste that may be occupied by evaporable water. These pores (exclusive of entrained air) are made up of two types: capillary pores and gel pores.

"Before hydration begins, and during the time when the paste remains plastic, a cement paste is a very weak solid held together by forces of interparticle attraction. [...] The water-filled spaces between the particles constitute an interconnected capillary system."

"With an average Type I cement, capillary pores will be present, even at ultimate hydration in any paste having an original water-cement ratio greater than about 0.44 by weight."

Concerning the size of pores, "...results of absorptivity tests indicate that the capillary pores are very much larger than the gel pores, except perhaps in pastes in which the gel nearly fills the available space."

"A saturated, hardened paste is permeable to water. Under a given pressure gradient and at a given temperature, the rate of flow is a function of the effective hydraulic radius of the pores and the effective porosity."

Cement gel can be characterized as having approximately the same degree of permeability as granite.

For pastes containing a lot of capillary space outside the gel, "...actual permeability exceeds the theoretical by a wide margin. This is believed to indicate that in such pastes the flow is predominantly in the relatively large capillary pores outside the gel."

"The permeability of concrete is generally greater than can be accounted for from the actual permeability of the paste...." Indications are "...that the water is able to flow through the fissures that develop under the aggregate during the bleeding period and thus to partially by-pass the paste."

The characteristic rate at which a dry specimen absorbs water is referred to as the absorptivity of the material. Tests have demonstrated that the initial absorption of water by a dried specimen occurs almost completely in the capillary spaces outside the gel.

"In a saturated, hardened cement paste, three classes of water are...recognized:
1. non-evaporable water
2. gel water, and
3. capillary water."

"Non-evaporable water is defined as that part of the total that has a vapor pressure of not over about 6×10^{-4} mm Hg at 23 °C (73.4 °F). It is a constituent of the solid material in the paste."

"The gel water is that contained in the pores of the gel. The pores in the gel are so small that most if not all the gel water is within the range of the van der Waal surface forces of the solid phase."

“The weight of gel water in a saturated paste is equal to $4V_m$, where V_m is the weight required to form a complete monomolecular adsorbed layer on the solid phase.”

“Like the gel water, the capillary water is really a solution of alkalies and other salts. The capillary water is that which occupies space in the paste other than the space occupied by the solid phase together with characteristic pores of the gel.”

It has been shown that almost all the capillary water in the paste is found beyond the range of the surface forces of the solid phase. “Hence, in a saturated paste, the capillary water is under no stress and its specific volume is the same as the normal specific volume of a solution having the same composition as the capillary water.”

In a partially saturated paste, the capillary water will experience some tensile stress. “This stress is due to curvature of the air-water interface and the surface tension of the water.”

“The quantity of gel water always bears a fixed ratio to the quantity of hydration products, whereas the quantity of capillary water is determined by the porosity of the paste.”

“Microscopic observation of hardened paste indicates that only $Ca(OH)_2$ crystals and unhydrated residues of the original cement grains can readily be identified.”

Examinations of the pores in the hardened paste with respect to size and volume “... indicate that the solid material is finely subdivided, though the solid units are obviously bonded to each other. [...] Since a gel is defined as a coherent mass of colloidal material, it follows that the principal constituent of hardened paste is a gel, called cement gel.”

The cement gel is a composition of the various products of the hydration process including all the principal oxides: CaO, SiO_2, Al_2O_3, and Fe_2O_3.

“When cement and water react, the total amount of heat evolved is directly proportional to the total amount of non-evaporable water in the paste.”

“The net heat of surface adsorption is the amount of heat in excess of the normal heat of liquefaction that is evolved when water vapor interacts with the solid phase.”

“Adsorption at low vapor pressures causes the solid phase to become covered with a film of water having a surface area presumably equal to the covered area of the solid phase. At pressures above $0.45p_s$ adsorption is accompanied by capillary condensation which progressively diminishes the exposed water-surface as the pressure is raised. The heat evolved from the destruction of water-surface is the net heat of capillary condensation.”

“The total net heat of adsorption is the sum of the total net heat of surface adsorption and the total net heat of capillary condensation.”

"Shrinking and swelling, moisture diffusion, capillary flow, and all other effects involving changes in moisture content of the paste at constant temperature are due to the free surface energy of the solid phase, or to the free surface energy of the water, or to both surface energies."

"Cement paste shrinks and swells as the cement gel loses or gains water. Swelling results when the surface forces of the solid phase are able to draw water into the narrow spaces between the solid surfaces."

"Shrinking results when water is withdrawn from the gel. It is probably due to the solid-to-solid attraction that tends to draw the solid surfaces together, though capillary tension and elastic behavior may also be involved."

The theory is that "...volume change is regarded as being the result of an unbalance in the forces acting on the adsorbed water. These forces are the solid-to-liquid attraction and capillary tension. When the solid-to-liquid attraction and capillary tension are equal, the volume of the gel remains constant."

"Swelling pressure is the force that would be just able to prevent water from entering the gel. [...] When the gel is composed of interconnected particles and encloses stable microcrystals and aggregate particles, as in concrete, shrinking or swelling is partially opposed by elastic forces."

"In a partially saturated paste the tendency of the water to enter the gel is opposed by tension in the capillary water."

As a cement paste experiences drying, capillary water and gel water are lost simultaneously. The resulting change in volume is caused solely by the change in gel-water content.

"If a specimen is kept sealed after its bleeding period, so that no extra water is available to it during the course of hydration, the pores in the paste will become partially emptied. This is called self-desiccation."

"Such self-desiccation is believed to be an important factor contributing to the frost resistance of concrete. Experimental evidence indicates that when specimens of good quality are stored in moist air, or even under water, they are unable to adsorb enough water to compensate completely for self-desiccation. Consequently, cement paste is seldom found in a completely saturated state, and hence is seldom in a condition immediately vulnerable to frost action."

An increasing temperature in a cement paste at constant water content will cause swelling to occur in addition to the normal thermal expansion.

"When counteracting effects are absent, evaporable water moves in the direction of descending temperature."

"In concrete subjected to changing external forces, changing temperatures, and fluctuating ambient humidity, the evaporable water must be in a continual state of flux. As a consequence, the concrete swells, shrinks, expands, and contracts under the changing conditions in a highly complicated way. The separate effects may combine in different ways at a given point in the mass so that they offset or augment each other. Possibly these effects have an influence on the ability of concrete to withstand weathering."

"The principal factors governing the ultimate degree of hydration, regardless of the time required, are the relative proportion of particles having mean diameters greater than about 50 microns, and the original water-cement ratio. [...] With any given cement the ultimate degree of hydration is proportional to the water content of the paste in all pastes in which w_o/c is less than a definite limiting value. With an average cement the limiting value is about 0.44 by weight; that is, this is the lowest w_0/c that will permit the ultimate degree of hydration with an average cement."

"With other factors equal, the average rate of hydration is lower the smaller w_0/c, except during a short initial period. Consequently, the time required to reach ultimate hydration becomes longer as w_0/c is made smaller.

During the early stages of hydration, say during the first week or two, the rate of hydration is higher by a large factor, the higher the specific surface. But during the later stages, the rates of hydration for cements of widely different specific surface differ comparatively little."

Self-desiccation effects will have an influence on the rate of hydration. Experiments show that "...sealed specimens hydrate more slowly than those having access to water, and they may never reach the ultimate degree of hydration possible when extra water is available. This has a bearing on the efficiency of membrane or seal-coat curing."

"Owing to the nature of the relationship between water content and free energy, ...the water in a saturated paste freezes or melts progressively as the temperature is varied below the normal melting point."

"The capillary water is believed to freeze in place, at least under the conditions of the experiments. However, the gel water probably flows or distills from the gel to the capillaries before it freezes." The temperature reading when the last increment of ice disappears on progressive melting is defined as the final melting point. "The final melting point in saturated pastes ranges from about -1.6 to about -0.05 °C (29.1 to about 31.9 °F). The depression of the final melting point is due to dissolved material in the mixing water, principally alkalies." In a specimen that is not fully saturated, the final melting point is affected by not only the dissolved material but also by the degree of saturation; the lower the degree of saturation the lower the final melting point. "All the evaporable water is freezable, but a minimum temperature of about -78 °C (-108.4 °F) is required to freeze all of it."

"At temperatures above -12 °C (10.4 °F), the maximum amount of freezable water is roughly proportional to the amount of capillary water...."

"For practical purposes, the freezable water can be considered to be identical with the capillary water. Hence, pastes that contain no capillary space outside the gel are considered to be without freezable water."

2.19 **Price, Walter H., FACTORS INFLUENCING CONCRETE STRENGTH, Journal of the American Concrete Institute, Vol. 22, No. 6, February 1951, pp. 417-432.**

"It is well-known that the strength of the concrete in the structure may be considerably different from that indicated by the 28-day control cylinders due to different curing conditions. Also, even if the structure and control cylinders were cured under identical conditions the control cylinders would not be completely indicative of the strength of the concrete in the structure because of differences in size, rate of loading, and lateral restraint."

"Usually where moisture is available for curing or where moisture contained in the concrete is not lost through drying, the strength development of the concrete will continue for a number of years. This later strength development adds to the safety of the structure but may be of little value where the structure has to support the full load at an early age. [...] In the case of reinforced concrete buildings which are usually not moist cured and where the members receive no moisture after construction, the concrete in the structure may never reach the strength indicated by the 28-day moist cured specimens. Designers should consider this in choosing working stresses."

Temperature and moisture both have major influences on the strength development of concrete. Laboratory tests show that "...the development of strength stops at an early age when the concrete specimen is exposed to dry air with no previous moist curing. Concrete exposed to dry air from the time it is placed is about 42% as strong at 6 months as concrete continuously moist cured. Specimens cured in water at 21 °C (70 °F) were found to be stronger at 28 days than those cured in a fog room at 100% relative humidity. The richer mixes showed better advantage than the leaner ones under water curing. The strength of the water-cured specimens was about 10% higher than the fog-cured specimens for concretes having water-cement ratios of 0.55 by weight. [...] Concrete in many buildings is not cured because of objections by the workmen to water dripping over the work and because curing compounds cannot be used due to the necessity of bonding the following lift or floor topping to the concrete already placed."

Curing temperatures are very important factors in the strength development of concrete. Results "...obtained on some Bureau of Reclamation projects showed the strength of the field control cylinders to be lower during the hot summer months than during the cooler months, even though they were moist cured at about 21 °C (70 °F) in every case. Apparently the concrete is weakened by very rapid setting which is not overcome by the subsequent curing at 21 °C (70 °F). Continued curing at higher temperatures for the full 28-day period...accelerated the strength development sufficiently to produce the highest strength for the highest temperature. At later ages, however, the specimens made and cured at higher temperatures had lower strengths than those made and cured at lower temperatures."

"The indicated strength of concrete made and cured under the same conditions is different when tested in cylinders of different height and diameter." Tests "...show the strength of a 900 mm (36 in) diameter cylinder as being only 82% that of a 150 mm (6 in) diameter cylinder. This difference is believed due to the possible faster strength gain of the smaller diameter cylinders." Test "...data indicate that large masses of concrete in a structure cannot be expected to approach the 28-day strength of concrete as indicated by a 150 x 300 mm (6 x 12 in) cylinder for a number of months."

"Specimens made in cardboard molds usually develop lower strengths than those made in steel molds. In...tests made in the Denver laboratories of the Bureau of Reclamation the compressive strength of specimens formed in cardboard molds was found to be about 3 ½ % less than companion specimens formed in steel molds."

2.20 **Timms, A. G., CURING OF CONCRETE, INTRODUCTION, Journal of the American Concrete Institute, Vol. 23, No. 9, May 1952, pp. 701-715.**

"Curing, as applied to the making of concrete, covers all the conditions both natural and artificially created that affect the extent and the rate of hydration of the cement."

With respect to moisture content, in the making and placement of concrete, curing refers to the various methods used to control moisture content or temperature of the concrete or both.

"In the early days of concrete making, speed in construction was not as important as it is today and the forms were left in place longer." Various methods are in use to keep concrete moist and also provide insulation against sudden temperature changes.

Curing plays a vital role on water-tightness. Sometimes the quantity of combined water in concrete can be doubled by using good curing practices in combination with favorable temperature conditions, thus greatly improving the degree of watertightness. For a given water-cement ratio, curing is the major factor in developing the potential strength of the concrete.

"Methods adopted from time to time for curing concrete may be classified as (a) those that supply water throughout the early hydration process and tend to maintain a uniform temperature, such as ponding, sprinkling, application of wet burlap or cotton mats, wet earth, sawdust, hay or straw, and (b) those designed to prevent loss of water but having little influence in maintaining a uniform temperature, as waterproof paper or impermeable membranes. Frequently a curing process is employed that combines the two."

"The optimum time to start moist curing is not easy to determine. It appears, in pavement practice, that the concrete should be allowed to subside in the forms and all free moisture disappear from the exposed surface before application of moisture or other forms of curing. [...] Sometimes the nature of the curing treatment dictates how soon after placing the concrete the curing may be applied."

T. C. Powers, in research conducted in 1947, "...has observed in the laboratory that if curing water is not supplied during the initial stages of rapid hydration some self-desiccation of the paste will result. Under these conditions subsequent applications of curing water will not restore the maximum degree of saturation."

Liquid membrane-forming curing materials have proven to be very popular in highway construction.

"Hydration reactions proceed more rapidly at higher temperatures, and hardening of concrete is greatly retarded as the temperature approaches the freezing point of water. Temperatures below 10 °C (50 °F) are considered unfavorable for curing, particularly if high early strength is desired. When concreting at temperatures below 21 °C (70 °F) it is desirable to use curing methods which tend to maintain suitable temperatures during the hardening period."

"Because of the importance of curing on the properties of concrete, it appears sound practice to require a certain minimum period of controlled moisture and temperature."

2.21 **Robinson, D. L., CURRENT PRACTICES FOR CURING CONCRETE PAVEMENTS, Journal of the American Concrete Institute, Vol. 28, No. 9, May 1952, pp. 705-711.**

"There are many methods and combinations of methods for curing concrete pavement slabs. Water curing, to replace water lost by evaporation, may be accomplished by periodic sprinkling, by ponding, or by saturated coverings of earth, hay, straw, cotton and jute mats, and multi-layered fabrics."

"The selection of curing methods is a matter of economics, just as is the selection of mix proportions and quality of aggregates." Various state requirements "...permit several methods from which a contractor may select the one that will be the least costly and will interfere least with his other operations, but which, in the opinion of the officials, still will give suitable results under the prevailing climatic conditions."

"Since membrane curing was simple to use and less costly than most other methods, the clear and light pigmented types were developed and, when permitted without initial burlap curing, came into almost exclusive use by contractors. [...] In 1947, T. C. Powers... reported that concrete sealed against evaporation must initially contain more than about 0.5 g of water per g of cement to assure full hydration, since self-desiccation progressively reduces the space available for hydration products."

"Theoretically, a covering of earth, straw, or mats has certain advantages over membranes for, in addition to maintaining a moisture supply, the cover acts as an insulating layer and minimizes detrimental volume changes induced by temperature variations."

2.22 **Gilkey, H. J., CURING STRUCTURAL CONCRETE, Journal of the American Concrete Institute, Vol. 28, No. 9, May 1952, pp. 711-715.**

"Ideal curing conditions for structural concrete differ in no way from those for similar mixtures in other adaptations. They are:

1. Continuously available free moisture at a sustained moderate temperature.

2. Freedom from stress that approaches closely the strength developed at time of its application.

3. Avoidance, upon termination of formal curing, of either rapid surface drying or of abrupt change of temperature (thermal shock) which would introduce damaging differential volume changes within the concrete.

4. Avoidance of exposure to freezing temperatures until curing has progressed far enough to partially empty the capillaries of their free moisture."

"Some special conditions surrounding structural concrete are:

1. That formal curing is about the only opportunity the concrete will have to cure since the conditions of use are rarely such as to supply subsequent moisture.

2. In cold weather concreting, temperature invariably presents a major problem.

3. With both vertical and horizontal surfaces it is difficult to supply the needed moisture to all parts of all the surfaces.

4. Early re-use of forms is generally of economic importance and complicates the problems of temperature, moisture retention and structural support. For beam-type

members, especially, adequate support and formal curing are important for a relatively long time."

2.23 **Waters, T., THE EFFECT OF ALLOWING CONCRETE TO DRY BEFORE IT HAS FULLY CURED, Magazine of Concrete Research, Vol. 7, No. 20, July 1955, pp. 79-82.**

"Except in cases where an early development of strength is required, it is not necessary to keep concrete wet after the initial curing period...." With respect to strength development, curing can be done at any time. When concrete is permitted to become dry for a period and is then re-wetted, experiments indicate that it will continue to increase in strength as if the dry period never existed.

"The experimental work was done in two parts, the first to find the effect of curing concrete in absolutely dry air, and the second in ordinary room atmosphere." For the first part, concrete with a water proportion by weight of 0.7 was used. For the second part, concrete with a water proportion by weight of 0.57 was used. Ordinary portland cement was used.

"Concrete indoors will not have sufficient moisture to give a reasonable rate of curing, and the concrete must be kept damp until it has cured sufficiently."

The results in this article would not apply to thin slabs of concrete, such as roads and walls. "Lack of moisture at an early age may lead to cracking and the concrete should be kept wet until it has developed sufficient strength to resist shrinkage cracks."

2.24 **Walker, Stanton and Bloem, Delmar L., EFFECTS OF CURING AND MOISTURE DISTRIBUTION ON MEASURED STRENGTH OF CONCRETE, Proceedings of the Highway Research Board, 36, 1957, pp. 334-346.**

"Flexural strength tests are being used to an increasing extent as a basis for specifying concrete quality and determining its acceptability. As a consequence, there is need for re-examining the many factors which affect the test results. One of the most critical of these is curing, not only as it affects the hydration of the cement but also through its influence on stresses induced within the specimen by non-uniform distribution of moisture."

"This study was conducted in several parts involving 384 tests for flexural strength. The principal divisions of the work were as follows:

A. Age-strength relationships for different curing conditions. Two coarse aggregates were used in air-entraining concretes of 3 cement factors. For each of the 6 conditions, specimens were made for flexural strength tests in triplicate at ages of 14, 28, 91 and 364 days for 4 curing conditions as follows: (1) continuously in the moist room; (2) continuously in saturated limewater; (3) 7 days in moist room followed by storage in room air until test; (4) 7 days in moist room followed by storage in room air until immersion in water 2 days before test.

B. Study of effect of resaturation on measured flexural strength of dry concrete. Air-entraining concrete with 6 sacks of cement per cubic yard was made with the 2 coarse aggregates. For each aggregate, 2 batches of 4 beams each, made on different days, provided tests in duplicate for all curing conditions. All specimens were cured in the standard moist room for 14 days, dried for 77 days at 38 °C (100 °F) and then tested for flexural strength after various periods of soaking, as follows: none; 30 minutes; 1, 2, 4, 8, 16 and 32 days.

C. Study of effect of drying on measured flexural strength of moist-cured concrete. For the same classes of concrete as in Part B, tests were made on specimens continuously moist-cured for 91 days and then air-dried at 38 °C (100 °F) for various periods before test, as follows: none; 30 minutes; 1, 2, 4, 8, 16 and 32 days. For each test condition, strengths were secured from 4 batches of concrete mixed on different days.

The data demonstrate the importance of moisture distribution and adequacy of curing to the reliability of tests for flexural strength of concrete."

"The concrete was designed to have a slump of 2 to 3 inches. An air content of 4.5±0.5% was secured by use of an admixture added at the time of mixing."

Summary and Conclusions

- "Continuous curing in the moist room and in limewater produced essentially the same strengths in both flexure and compression. Normal increases in strength with age were shown."

- "Drying test specimens in laboratory air after 7-day moist curing produced large reductions in strength for ages at test of 14 and 28 days----up to 36% at 14 days. At 91 days, the difference in strength ranged between relatively small increases and relatively small decreases and, on the average, amounted to a reduction of 7 percent below standard moist-curing."

- "Immersion for 48 hours of dried specimens overcome the strength reductions due to drying for test ages of 14 and 28 days. At 91 days the immersed and dried specimens gave the same strength."

- "Increases in cement content produced normal increases in measured flexural strength of moist-cured specimens. For the air-dried concrete additional cement resulted in no increase in strength. For the re-immersed specimens, there was some benefit due to adding cement but it was relatively small."

- "Specimens which had been moist cured 14 days and then stored in air at 38 °C (100 °F) for 77 days, showed sharply reduced flexural strengths when immersed in water. After 4-day immersion a slight gain in strength was found which continued at a low rate during the 32-day immersion and which may have been due to continuing hydration of cement."

- "Specimens cured moist for 91 days and then dried at 38 °C (100 °F) showed large reduction in flexural strength, up to about 40% after 4 days of drying. Thereafter, there was a slight increase in measured strength up to the maximum period of 32 days' drying."

This reported study "...demonstrates the great sensitivity of flexural strength tests to variations in curing and moisture condition of the specimens."

2.25 CURING CONCRETE, Journal of the American Concrete Institute, Vol. 30, No. 2, August 1958, pp. 161-172.

This was a report by ACI Committee 612, which was addressing curing requirements during the late 1950s. This is apparently the first report by an ACI committee in the ACI Journal dealing exclusively with curing requirements of concrete.

The report contains a definition of *optimum curing*. It says "...optimum curing is defined as the act of maintaining controlled conditions for freshly placed concrete for some definite period following the placing or finishing operations to assure the proper hydration of the cement and the proper hardening of the concrete."

"Control of temperature throughout the curing period is desirable, but except for certain structures, it is less essential than other requirements."

The report lists five basic curing requirements:

1. "The preservation of an adequate water content in the concrete.
2. The maintenance of the temperature of the concrete at some value above freezing as constantly as may be practicable during the curing period.
3. The preservation of a reasonably uniform temperature throughout the whole body of the concrete.
4. The protection of the structure from damaging mechanical disturbance, particularly load stresses, heavy shock, and excessive vibration especially during the early portion of the curing period.
5. The passage of time for the hydration of the cement and hardening of the concrete to the degree necessary for the safe use of the article or structure which it forms."

"Preservation of the moisture content of the concrete may be accomplished by any of several methods or by a combination of two or more methods. The surface of the concrete may be kept wet with water, or loss of moisture may be prevented or restricted by the application of impervious coatings, membranes, or coverings, or by the retention of forms."

"Protection against high temperatures is somewhat of a complex procedure as the excessive temperature of the concrete may be derived from any one or all of three sources: the temperature of the surrounding atmosphere, absorption of solar heat, and the heat of hydration of the cement."

"Logically, the ideal curing temperature for a given concrete installation or structure may be a few degrees below the average temperature to which the concrete will be exposed during its period of service. [...] The drop in temperature during the first 24 hr after curing ceases should be no more than 16.7 °C (30 °F) for mass concrete or 27.8 °C (50 °F) for thin sections."

"Early progress of the hydration of the cement in the concrete is indicated by the setting or solidifying and finally the hardening of the mass. Continuous mechanical disturbance of the concrete during this process will result in the failure to form the integral solid intended in the design of the structure, and the member or structure will fail to attain the strength for which it was designed."

"The amount of time required for the concrete to attain the strength desired for safe use or to attain the desired degree of hardness varies with the temperature at which the concrete is cured, the rate of hydration of the cement used, and the availability of moisture for hydration of the cement."

"Considerable effort has been expended in studies of methods for shortening the curing period. As a consequence it has been determined that provision may be made in some work for shortening the curing period through the use of accelerators in the concrete, through the use of cements having a high rate of hydration, or through elevation of the temperature to a value near the upper extreme of the acceptable range of temperatures."

"Optimum practice for curing horizontal units: pavements, sidewalks, canal linings, small docks, and building floors[:]

Initial curing----Immediately after the finishing operations are completed, the concrete should be covered with two thicknesses of an approved woven fabric, a quilted fiber mat, or other covering of an approved absorptive material thoroughly saturated with water when placed. [...]

Final curing---- An acceptable curing agent for application after the initial curing period and for the final curing period may be chosen from the following list.

- The covering used in the initial curing period kept in place and in the same condition as for the initial curing period.
- Two inches of moist earth or sand evenly distributed over the surface of the concrete and kept thoroughly saturated by spraying with water.
- Three inches of moist hay, grass, or clean straw uniformly distributed over the concrete and kept wet by a water spray.
- Approved impervious light colored paper or plastic coverings placed and maintained in contact with the surface of the concrete.
- Approved impervious coatings which may be developed from liquid compounds sprayed on the surface of the concrete. [...]

Temperature----When the temperature of the atmosphere is 4.5 °C (40 °F) or more, the final curing agents should remain in place for at least 72 hr and for such additional length of time as may be required for job cured specimens to have attained the compressive or flexural strength required of the concrete at the age tested."

"Optimum curing for vertical units: walls, small piers, columns, floors, roofs, small dams, and small abutments wherein the least dimension is less than 0.61 m (2 ft)[:]

Initial curing---- Immediately after the finishing operations are completed or upon cessation of placing operations for a period of more than 3 hr, the exposed surface of the concrete should be covered with two thicknesses of an approved woven fabric, an approved quilted fiber blanket, or other cover of highly absorptive material thoroughly wet with water when applied. [...] This covering should remain in place for at least 96 hr. [...]

Final curing----Upon removal of the wet coverings used for the initial curing, any one of the following methods for final curing practical or desirable in a given project may be used.

- Application of a continuous mist spray of water directly on the concrete.
- Application of an approved impervious paper or plastic covering directly upon the surface of the concrete.
- Application of an approved impervious coating material upon the concrete.
- Application of a layer of wet sand at least 50 mm (2 in) thick (top of horizontal portions only).

Temperature----When the temperature of the surrounding air is 4.5 °C (40 °F) or more the total length of curing period should be at least 10 days, the initial curing period at least 4 days, and a final curing for the remainder. [...] When the mean daily temperature of the surrounding air is less than 4.5 °C (40 °F), the concrete should be so protected as to maintain within it a temperature of at least 10 °C (50 °F) to 21 °C (70 °F) for the curing period."

2.26 **Powers, T. C., Copeland, L. E., and Mann, H. M., CAPILLARY CONTINUITY OR DISCONTINUITY IN CEMENT PASTES, Journal of the Research and Development Laboratories, Vol. 1, No. 2, Portland Cement Association, May 1959, pp. 38-48.**

The synopsis for this article states: "This is a study of the capillary structure of cement paste in terms of data on permeability to water."

"Under various circumstances it is important to reduce the rate of penetration of concrete by water as much as is practically possible. For example, this is true with respect to concretes subject to frost action."

"Other uses where pastes with continuous capillaries should be avoided include reinforced concrete in or near the sea."

"Concrete subject to attack by aggressive waters, or to the leaching of soft water, obviously should not contain a paste with continuous capillaries."

"Preclusion of continuous capillaries in the paste is a matter of selection of water-cement ratio of the fresh paste and control of curing conditions. [...] The length of curing required...will...depend mostly on prevailing temperatures and characteristics of the cement. Under standard laboratory conditions, the required time for an ordinary Type I cement might be about as shown in the following table:

W/C	Time Required
0.40	3 days
0.45	7 days
0.50	14 days
0.60	6 months
0.70	1 year
>0.70	Impossible"

Some of the major conclusions from this study are:

- "Capillaries in fresh paste are defined by the cement particles and are continuous. Hydration of cement increases the solid content of the paste, and if it is increased sufficiently, the original capillaries become blocked by gel, and capillary cavities are thus created."

- "For any given cement, there is a maximum water-cement ratio above which complete hydration does not produce enough gel to block all the capillaries. For a Type I cement the limiting W/C ratio (by weight) was about 0.7.... [...] Recommended practice for producing good concrete is...to eliminate continuous capillaries from the paste."

- "At water-cement ratios below the maximum at which discontinuity can be produced, capillaries become discontinuous before all of the cement has become hydrated."

- "Pastes containing continuous capillaries should not be permitted in concrete used where the lowest possible rate of penetration of water is needed. Such uses include most structures subject to frost action, or subject to aggressive waters, or to leaching, and reinforced concrete used in or near the sea."

2.27 **Bloem, D. L., CONCRETE STRENGTH MEASUREMENT--CORES VERSUS CYLINDERS, Proceedings, American Society of Testing Materials, Volume 65, 1965, pp. 668-696.**

"Design of any reinforced concrete structure assumes a value for strength of the concrete which then becomes a principal criterion of acceptability. Strength measurements are expected generally to exceed the design value, f_c'. The concrete is sampled at the time of delivery and tested under highly standardized conditions. If an appropriately large proportion, usually either 80 or 90 per cent, of the tests exceeds f_c', the concrete is considered to meet the strength requirements. Even though the prescribed treatment of the test specimens is more favorable to strength development than that likely to prevail on the job, experience has shown this system to be adequately protective. Obviously it can be depended upon only if reasonably good practices for handling, placement, protection, and curing of the concrete in the structure are enforced."

"Although controversy over concrete strength seems inevitable, it is worthwhile to examine the relationships among various measures of that property. [...] If the standard conditions for acceptance tests are taken as the basis of comparison, deviation from the standard in an effort to simulate field protection and curing or for other reasons will affect measured strength as follows:

(1) Deficiency of moisture will decrease strength development. [...]

(2) With adequate moisture, sustained low temperature (above freezing) will reduce strength at usual test ages but increase ultimate strength potential.

(3) High temperatures will accelerate rate of strength development, but limit maximum strength levels."

Based upon extensive research and analyses of core test data, research has shown:

(1) "specimens from finished structures averaged about 90 per cent of the strength of similar standard specimens, with some as low as 65 to 75 per cent ;

(2) strengths of cores from columns averaged 12 per cent lower when drilled horizontally than when drilled vertically (the latter corresponding to the direction of actual loading);

(3) calculations from actual loading tests showed concrete strength in columns averaging about 68 per cent of cube strength (roughly 85 per cent of cylinder strength), but as low as 56 per cent (about 65 per cent of cylinder);

(4) the concrete in the uppermost portion of a column was weaker, by from 1 to 27 per cent depending upon the type of concrete, than that in the lower portions."

The purpose of this paper was to report on research designed to develop relationships among the common measures of concrete strength.

Some conclusions from this research were:

- "The investigation confirmed the long recognized fact that standard strength tests of molded cylinders are useful primarily as an index to concrete quality. They are not a direct or quantitative measure of strength in place. The strength of cores removed from a structure will vary greatly depending upon adequacy of its curing and treatment of the test specimens."

- "Core strength in columns made with relatively low-slump air-entrained concrete was found to be nearly constant throughout the height except for the top few inches, where it was considerably lower. Other investigations have shown that cores drilled horizontally from columns...test lower than ones drilled vertically, giving a pessimistic picture of strength in the direction of loading."

- "Molded cylinders cured to simulate conditions in the structure provide an indication, at least relatively, of environmental effects on strength." In the research for this paper, "...the field-cured cylinders tested at 28 days produced strengths agreeing fairly well, on the conservative side, with cores tested after air-drying to the approximate moisture condition of the structure."

In the article's closing statement, the author states that "...when reasonable care has been taken to handle and cure the structure properly, acceptance on the basis of standard tests has seemed to provide ample strength in place. Core tests made to check adequacy of strength in place must be interpreted with judgment. They cannot be translated to terms of standard cylinder strength with any degree of confidence, nor should they be expected necessarily to exceed the specified strength, f_c'."

2.28 **Bloem, Delmar L., CONCRETE STRENGTH IN STRUCTURES, Journal of the American Concrete Institute, Vol. 65, No. 3, March 1968, pp. 176-187.**

"The use of strength tests of standard-cured molded cylinders for control purposes and for checking the acceptability of concrete as produced is well established." Research has demonstrated "...that the standard tests do not provide a quantitative measure of concrete's load-carrying capacity in place."

"Strength in place as measured on drilled cores will be less than that of moist-cured molded cylinders tested at the same age and will probably never reach the standard 28-day strength even at greater ages. The amount of the deficiency will depend on the efficiency of field curing and will be affected by the type of cement. Other influences... such as the effect of precipitation on concrete outdoors, may alter or even reverse the relationship between cores and cylinders."

"Core tests used to check apparent deficiencies in strength indicated by standard cylinders must be interpreted with caution. In many cases cores will not attain the specified strength level, f_c', on which design calculations were based. This should probably not be cause for alarm unless the deficiency is excessive. Design formulas provide a large safety margin sufficient to allow for the fact that field concrete will not be as favorably protected and cured as standard test specimens. When cores are lower than f_c', it simply means that some of that margin of uncertainty has been used. Core tests equaling 75 percent of f_c' provide an excess over calculated working stress of 67 percent , which should be much more than adequate in most cases. Usually, however, cores should not test that low if field practices are proper and overdesign of average strength is adequate."

"Field-cured cylinders may provide useful information but do not quantitatively reflect core strength." Tests indicated "...the latter averaged about 10 percent less than field-cured cylinders for good curing but 21 percent less for poor curing. Thus the field-cured cylinders may be misleading in that they are less adversely affected by improper curing than the structure itself."

"Push-out cylinders cast in the slabs provided a fairly reliable measure, relatively, of core strengths. The cores, however, averaged about 7 percent lower. Unlike field-cured cylinders, the push-outs related consistently to cores irrespective of adequacy of curing."

Under the conditions of meticulous care in testing used in the research reported in this article, "...all three methods of measuring strength—molded cylinders, push-out cylinders, and cores—were sufficiently reproducible to provide confidence in results consisting of averages for three specimens."

3. LITERATURE FROM 1970 TO 1990

3.1 **Neville, A. M., PROPERTIES OF CONCRETE, John Wiley and Sons, Chapter 5, "Strength of Concrete," 1973, pp. 233-308.**

From the section on Curing of Concrete:

"Curing is the name given to procedures used for promoting the hydration of cement, and consists of a control of temperature and of the moisture movement from and into the concrete."

The author states that "...the object of curing is to keep concrete saturated, or as nearly saturated as possible, until the originally water-filled space in the fresh cement has been filled to the desired extent by the products of hydration of cement. In the case of site concrete, active curing stops nearly always long before the maximum possible hydration has taken place."

"The necessity for curing arises from the fact that hydration of cement can take place only in water-filled capillaries. For this reason, a loss of water by evaporation from the capillaries must be prevented. Furthermore, water lost internally by self-desiccation has to be replaced by water from outside, i.e., ingress of water into the concrete must be made possible."

It is known that "...hydration of a sealed specimen can proceed only if the amount of water present in the paste is at least twice that of the water already combined. Self-desiccation is thus of importance in mixes with water/cement ratios below about 0.5; for higher water/cement ratios the rate of hydration of a sealed specimen equals that of a saturated specimen. It should not be forgotten, however, that only half the water present in the paste can be used for chemical combination; this is so even if the total amount of water present is less than the water required for combination. This statement is of considerable importance as it was formerly thought that, provided a concrete mix contained water in excess of that required for the chemical reactions with cement, a small loss of water during hardening would not adversely affect the process of hardening and the gain of strength. It is now known that hydration can take place only when the vapor pressure in the capillaries is sufficiently high, about 0.8 of the saturation pressure. Hydration at a maximum rate can proceed only under conditions of saturation." [...] It has been shown that "...below a vapor pressure of 0.8 of the saturation pressure the degree of hydration is low, and negligible below 0.3 of the saturation pressure."

Concerning concrete quality, "...the quality of concrete depends primarily on the gel/space ratio of the paste. If, however, the water-filled space in fresh concrete is greater than the volume that can be filled by the products of hydration, greater hydration will lead to a higher strength and a lower permeability."

Methods of Curing:
"Once the concrete has set, wet curing can be provided by keeping the concrete in contact with a source of water. This may be achieved by spraying or flooding (ponding), or by covering the concrete with wet sand or earth, sawdust or straw."

"Another means of curing is to use an impermeable membrane or waterproof paper. A membrane, provided it is not punctured or damaged, will effectively prevent evaporation of water from the concrete but will not allow ingress of water to replenish that lost by self-desiccation."

"Except when used on concrete with a high water/cement ratio, sealing compounds reduce the degree and rate of hydration compared with efficient wet curing. However, wet curing is often applied only intermittently so that in practice sealing may lead to better results."

"The period of curing cannot be prescribed simply but it is usual to specify a minimum of seven days for ordinary portland cement concrete."

"High-strength concrete should be cured at an early age as partial hydration may make the capillaries discontinuous: on renewal of curing, water would not be able to enter the interior of the concrete and no further hydration would result."

Maturity of Concrete:
When considering temperature, the author states: "The temperature during curing controls the rate of progress of the reactions of hydration and consequently affects the development of strength of concrete."

"Since strength of concrete depends on both age and temperature we can say that strength is a function of Σ(time x temperature), and this summation is called maturity."

Graphical analysis shows that "...strength plotted against the logarithm of maturity gives a straight line. It is...possible to express strength at any maturity as a percentage of strength of concrete at any other maturity...."

When considering high temperatures, "...early high temperature leads to a lower strength for a given total maturity than when heating is delayed for at least a week or is absent."

Results indicate that "...the maturity rule applies fairly well when the initial temperature of concrete is between 16 and 27 °C (60 and 80 °F) and no loss of moisture by drying takes place during the period considered."

Influence of Temperature on Strength of Concrete:
Tests show "...that a rise in the curing temperature speeds up the chemical reactions of hydration and thus affects beneficially the early strength of concrete without any ill-effects on the later strength. However, a higher temperature during placing and setting, although it increases the very early strength, may adversely affect the strength from about 7 days onwards. The explanation is that a rapid initial hydration appears to form products of a poorer physical structure, probably more porous, so that a large proportion of the pores will always remain unfilled." It follows "...that this will lead to a lower strength compared with a less porous, though slowly hydrating, paste in which a high gel/space ratio will eventually be reached."

When calcium chloride is added to a concrete mix, the detrimental effects of high temperature which occur during setting can be mitigated.

"The increase in strength caused by the addition of calcium chloride depends on the temperature of the concrete and is proportionately greater at lower temperatures."

Tests have shown "...that there is an optimum temperature during the early life of concrete that will lead to the highest strength at a desired age. For laboratory-made concrete using ordinary or modified portland cement the optimum temperature is approximately 13 °C (55 °F); for rapid hardening portland cement it is about 4 °C (40 °F)."

A concrete placed in summer weather can be expected to have a lower strength than a similar mix placed during the winter season.

Steam Curing at Atmospheric Pressure:
"Since an increase in the curing temperature of concrete increases its rate of development of strength, the gain of strength can be speeded up by curing concrete in steam. [...] Concrete with a lower water/cement ratio responds to steam curing much better than a weaker mix."

Steam curing is used primarily with precast products.

"The temperature history of the interior of the concrete being cured is not the same as that at the surface. The rise in temperature at the centre [sic] is slower but the rate of cooling is lower, too. Thus the area under the temperature-time curve is approximately the same for the interior and for points near the surface of the concrete block, so that all parts of the concrete have the same maturity."

High-pressure Steam Curing:
"Since pressures above atmospheric are involved, the curing chamber must be of the pressure vessel type with a supply of wet steam; excess water is necessary as superheated steam must not be allowed to come into contact with the concrete. Such a vessel is known

as an autoclave, and...high-pressure steam curing is often referred to as autoclaving."

"In the field of concrete, high-pressure steam curing is usually applied to precast products (made both of ordinary and lightweight concrete) when any of the following characteristics are desired:

(a) high early strength: with high-pressure steam curing the 28-day strength on normal curing can be reached in about 24 hours;
(b) high durability: high-pressure steam curing improves the resistance of concrete to sulfates and to other forms of chemical attack, also to freezing and thawing, and reduces efflorescence; and
(c) reduced drying shrinkage and moisture movement."

"Because of the microcrystalline character of the cement paste, high-pressure steam-cured concrete has a considerably reduced shrinkage, about $\frac{1}{6}$ to $\frac{1}{3}$ of that of concrete cured at normal temperatures."

"The products of hydration of cement subjected to high-pressure steam curing, as well as those of the secondary lime-silica reactions, are stable, and there is no retrogression of strength. At the age of one year the strength of normally cured concrete is approximately the same as that of high-pressure steam-cured concrete of similar mix proportions."

"On the debit side, high-pressure steam curing reduces the strength in bond with reinforcement by about one-half compared with ordinary curing so that the application of steam to reinforced concrete members is considered inadvisable."

Variation in Strength of Cement:
"Although on a site it is difficult to isolate the influence of cement, there is no doubt that the inherent variation in the strength of cement is reflected in the variation in the strength of concrete."

3.2 **Carrasquillo, Ramon L., Slate, Floyd O. and Nilson, Arthur H., MICROCRACKING AND BEHAVIOR OF HIGH STRENGTH CONCRETE SUBJECT TO SHORT-TERM LOADING, Journal of the American Concrete Institute, Vol. 78, No. 3, May-June 1981, pp. 179-186.**

While not directly related to curing, this paper provides an understanding of the stress-strain behavior of high-strength concrete. It is therefore included in this bibliography.

In describing failure under uniaxial compression, the authors provide the following:
"The development of combined cracks, consisting of combinations of bond and mortar cracks, was found to be an essential step in progression toward impending failure. Such cracks must be identified and studied to understand the failure mechanism of concrete. Normal strength concretes start to develop combined cracks at about 70 percent of strain

at maximum load, and thus are approaching instability and impending failure, while high strength concrete does not develop significant combined cracks until about 90 percent or more of strain at maximum load. High strength concrete has much less microcracking at all load levels than normal strength concrete, but fails more suddenly with fewer planes of failure."

"The purpose of this study was (1) to record and compare the type, extent, and progress of internal microcracking of plain concrete concentrically loaded in short-term uniaxial compression, and (2) to explain differences in the mechanical properties of different strength concretes in terms of the formation and propagation of microcracks."

This study was "...limited to normal weight concretes made using conventional production techniques and containing limestone or gravel coarse aggregates, for strengths from about 31 to 76 MPa (4,500 to 11,000 psi)."

The following conclusions are given in the article:

"Microcracking study:

1. The bond-mortar crack classification system, useful in studying behavior of normal strength concrete, is not highly relevant for the study of mechanisms leading to failure of higher strength concretes. The classification of microcracks into simple and combined cracks, and the distinction between different types of combined cracks, is more appropriate.
2. For higher strength concretes, the strain at which an unstable progressive crack growth mechanism occurs is indicated by a significant increase in length and number of combined cracks.
3. For higher strength concrete, a higher percent of the combined cracking consists of a stable type of crack, and there is no significant progressive combined cracking at any of the strains considered, up to incipient failure.
4. The number of potential failure planes at any given strain is significantly less for higher strength concretes, and the internal microcracking behavior approaches that of a homogeneous material.
5. This study indicates that high strength concrete can be loaded to a higher stress-strength ratio without initiating a self-propagating mechanism leading to disruptive failure; i.e., the sustained-load strength is a higher percentage of the short-term strength.

Stress-strain behavior:

1. For higher strength concretes there is less bond cracking than for lower strength concretes, and the stress-strength ratio at which microcracks begin to form continuous crack patterns is higher. Therefore, the stress-strain curve is steeper and more linear to a higher stress-strength ratio.
2. There are fewer continuous crack paths at incipient failure for higher strength concretes, in most cases only one. This results in an increase in the rate of change of curvature of the stress-strain curve close to the maximum stress.

3. The smaller number of continuous crack paths for higher strength concretes results in a decrease in the redundancy of the material. This is an explanation for the absence of a stable descending branch in the stress-strain curve for higher strength concretes.

Failure mode in uniaxial compression:
1. A tensile or tensile-shear failure mechanism is the most relevant crack mechanism controlling failure of concrete in uniaxial compression. Failure of concrete in uniaxial compression occurs in a direction parallel to the direction of the applied load for all the concretes tested.
2. Normal strength concretes develop highly irregular failure surfaces including a large amount of bond failure.
3. Medium strength concretes develop a mechanism similar to the normal strength concretes but at a higher strain.
4. The failure mode of high strength concretes is typical of that of a nearly homogeneous material. Failure occurs suddenly in a vertical, nearly flat plane passing through the aggregate and the mortar."

3.3 CONCRETE MANUAL, A WATER RESOURCES TECHNICAL PUBLICATION, Chapter VI--Handling, Placing, Finishing, and Curing, Section E. Curing and Section F. Concreting Under Severe Weather Conditions, U. S. Department of the Interior, Eighth Edition, Revised, 1981, pp. 375-391.

Moist Curing:
"The object of curing is to prevent or replenish the loss of necessary moisture during the early, relatively rapid stage of hydration. The usual procedure for accomplishing this is to keep the exposed surface continuously moist by spraying or ponding, or by covering with earth, sand, or burlap maintained in a moist condition. [...] Early drying must be prevented or the concrete will not reach full potential quality. In warm, dry, windy weather, corners, edges, and surfaces become dry more readily. If these portions are prevented from drying and fully develop hardness and quality, interior portions will have been adequately cured."

It is stated that "...specifications usually require that concrete, which is to be water cured, shall be kept moist at least 14 days. [...] Tests indicate that a period of drying after completion of moist curing considerably enhances the resistance of concrete to sulfate attack, probably as a result of carbonation."

"Wood forms left in place provide good protection from the sun, but will not keep the concrete sufficiently moist to be acceptable as a method of moist curing for outdoor concrete. However, the surfaces of ceilings and inside walls require no curing other than that resulting from forms being left in place for at least 4 days."

Curing With Sealing Membranes:
"The membrane may be an impermeable plastic sheet placed over the surface or a film

formed by application of liquid materials (curing compounds) to the surfaces. [...] Laboratory test and field observations indicate that an effective membrane kept intact for 28 days provides the equivalent of 14 days' continuous moist curing."

Curing compounds are usually sprayed on the surface of the concrete.

"Proper care of a concrete surface prior to compound application is highly important. Beginning promptly after form removal, formed surfaces should be saturated with a fine spray of water until they will absorb no more water. Thereafter, the surfaces should be moistened frequently to maintain continuous curing through the interval after form loosening and stripping and before the compound is applied. The compound is then applied as soon as the free moisture on the surface has disappeared. On unformed surfaces, the compound should be applied immediately after the bleeding water or shine disappears, leaving a dull appearance."

The continuity of curing membranes should be carefully maintained for a minimum of 28 days to be fully effective.

Sheet plastic is frequently used in the curing of slabs and structural shapes. Specifications will usually require this type of membrane material be maintained for at least 14 days.

Precautions to be Observed During Hot Weather:
"Although attention to curing requirements is important at all times, it is especially so in hot, dry weather because of the greater danger of...cracking. Higher temperatures with low humidity cause sprinkled surfaces to dry faster and to require more frequent sprinkling; hence, the use of wet burlap and other means of retaining the moisture for longer periods becomes increasingly desirable."

Precautions to be Observed During Cold Weather:
Concrete gains strength much slower at low temperatures. "For this reason,... specifications require that concrete be protected against freezing temperatures for at least 48 hours after being placed when the mean daily temperature is 4.5 °C (40 °F) or above. They also provide that when the mean daily temperature is below 4.5 °C (40 °F) concrete should have a temperature of not less than 10 °C (50 °F) and should be maintained at not less than 10 °C (50 °F) for at least 72 hours."

3.4 Senbetta, Ephraim and Scholer, Charles F., A NEW APPROACH FOR TESTING CONCRETE CURING EFFICIENCY, Journal of the American Concrete Institute, Vol. 81, No. 1, January-February 1984, pp. 82-86.

In this article, the authors propose an approach to measuring curing efficiency based on changes in absorptivity at different depths of a sample. The idea proposed is "...that if a sample is adequately cured, it will have approximately the same pore structure at the surface region as that farther beneath the surface, and in the case of poor curing, the opposite would be true."

"The results [of this study] showed significantly large changes in absorptivity of the paste between the surface and the bottom regions of poorly cured samples and negligible changes for well-cured samples."

Based on these differences in absorptivity values, a quantitative dividing line between adequate and inadequate curing can be determined.

The authors concluded "...that a better approach for evaluating how well concrete is cured is looking at some measurable physical property of the concrete itself, and not just the materials used for curing the concrete."

"It is believed that the solid materials in hardened cement paste normally occupy 45 to 60 percent of the total volume of the paste, and the average porosity is 40 to 55 percent." [...] Concerning the importance of curing, "...next to water-cement ratio, proper curing of the paste has the greatest influence on its porosity, especially the porosity at the surface region."

With respect to permeability, "...at a given age, other than water-cement ratio, the degree of hydration of the cement, i.e., the extent of the curing, has the strongest influence on the permeability of the paste."

"In dealing with permeability, the presence of capillary pores is of prime interest because cement paste is 20 to 100 times as permeable as cement gel, and therefore, the gel pores have a very minor role to play."

In this study "...slabs were cured under five different conditions:

1. covered with wet burlap
2. covered with plastic sheet
3. coated with curing compound that was later found to be poor quality
4. left exposed
5. left exposed in a windy environment"

The slabs were made of mortar with a water-cement ratio of 0.50 and a sand-cement ratio of 2.74. Curing periods varied from one to five days, and the slabs were exposed subsequently to air at 22, 44, and 72 percent RH.

The results, as expected, were "...the more effective the curing (as was the case with the wet burlap and plastic cover), the smaller the difference in the absorptivity between the top and bottom regions, and large changes in absorptivity were observed for the ineffective curing methods." Tests showed "...that the absorptivity of the surfaces of the poorly cured samples was approximately six times that of the well-cured samples."

"Based on differences in absorptivity values at depths of 1 and 6 cm (0.39 and 2.36 in.), with a 97.5 percent confidence, it was determined that a difference of $\leq 3.7 \times 10^{-6}$ cm^2/sec (0.57×10^{-6} in^2/sec) was indicative of adequate curing and a difference of $\geq$ 5.5×10^{-6} cm^2/sec (0.85×10^{-6} in^2/sec) was an indication of inadequate curing."

Conclusions are:

- "The absorptivity test is a simple, sensitive, and quick measure of the extent of cement hydration and the resulting pore structure of the paste in mortar samples."
- "Poor curing affects only the exposed surface for a depth of approximately 3 cm (1.18 in.) for the worst atmospheric and curing conditions encountered in this study."
- "The use of absorptivity differences between two different zones, such as the tops and bottoms of slabs, to determine the effect of curing practices may be applicable regardless of mix proportions because the quantity of interest is the difference between two zones of the same sample."

3.5 **RESEARCH NEEDS FOR HIGH-STRENGTH CONCRETE, Reported by ACI Committee 363, ACI Materials Journal, Vol. 84, No. 6, Nov-Dec 1987, pp. 559-561.**

The following statements are related to curing:

"The properties of high-strength concretes [HSC] are frequently determined based on specimens cured in an ideal laboratory environment. Information on the effect of curing procedures used in the field are needed to develop greater confidence in the use of the material. Field conditions would simulate the environmental changes as well as the heat of hydration effects produced by the concrete mass."

"Evaluations should include the use of different chemical and mineral admixtures to produce the high-strength concretes and the effects of these admixtures on mechanical properties and durability over a long period of time. The role of mineral admixtures, such as silica fume, for a high-strength concrete should be carefully examined."

Construction with HSC has been hampered by the lack of general information on the safe and economical use of this material in the field.

3.6 **Maage, Magne and Sellevold, Erik J., EFFECT OF MICROSILICA ON THE DURABILITY OF CONCRETE STRUCTURES, Concrete International, Vol. 9, No. 12, December 1987, pp. 39-43.**

This paper reports on cores taken from concrete structures both with and without microsilica (silica fume). The cores were tested by mechanical and microscopic methods. The test results showed no significant detrimental changes in the long-term structural properties of concrete containing microsilica. With respect to carbonation, "...the microsilica concretes showed greater variation [between mean values of carbonation for the two types of concretes—with and without microsilica], possibly a consequence of the greater sensitivity of this type concrete to early curing conditions."

3.7 **Senbetta, E. and Malchow, G., STUDIES ON CONTROL OF DURABILITY OF CONCRETE THROUGH PROPER CURING, Concrete Durability, Katharine and Bryant Mather International Conference, SP-100, American Concrete Institute, 1987, pp. 73-87.**

"The objective of this study was to develop test data which show the impact of curing on the properties of concrete that are related to durability. These properties include the degree to which concrete resists abrasion, the resistance to corrosion of reinforcing steel, resistance to scaling, volume stability, and pore structure development as measured by absorptivity method. A secondary objective of this study was to compare the effect of different curing methods on durability, including differences in performance between different curing compounds."

"Assuming that a piece of concrete is made from a well proportioned mix using suitable materials and employing adequate placing and finishing techniques, the curing of the concrete has the greatest influence in the porosity and permeability of the concrete, and hence, on its durability and strength at the surface region. Unfortunately, proper curing is one of the most neglected steps in the construction process. One estimate is as much as 24% of all the concrete placed in nonresidential construction alone in the United States in 1979 was not cured at all, and only as little as 26% was cured according to job specifications." The situation is probably not any better today.

The authors state that "...next to the water to cement ratio, proper curing of the paste has the greatest influence on the porosity of the paste and especially the porosity of the paste at the surface region."

"For a given concrete mix proper curing is key to reducing porosity and measures to reduce drying shrinkage or to compensate for the expected shrinkage have been shown to diminish cracking."

The curing conditions considered in this study included: "moist curing in a 100% relative humidity room, completely sealing the surface using resin modified paraffin wax,...applying a fairly good quality curing compound ..., applying a relatively poor quality curing compound ..., and covering with plastic sheet. Air drying without the use of any curing material was the control."

Concrete for the various test specimens had a water-cement ratio of 0.67. The curing materials were applied soon after bleed water had evaporated from the surface.

Specimens were cast to evaluate abrasion resistance, drying shrinkage, corrosion activity, chloride ion concentration, and absorptivity.

With respect to shrinkage after seven days, "...the drying shrinkage of the well protected specimens was only 20% of the poorly cured specimens."

It was evident that "...the less effective the curing, the more permeable the concrete surface, and the higher the chloride ion concentration resulting in greater corrosion. Compared to the well cured concrete the chloride ion concentration of the poorly cured concrete was found to be nearly 50% higher."

"For a given water-cement ratio, if the absorptivity is high, it indicates poor curing and high porosity." [...] It should be noted that "...neglecting the curing of concrete can increase its surface absorptivity anywhere from six to ten times of what it would have been if steps were taken to insure proper curing."

"The conclusions from this study are...:

1. Proper curing can increase the abrasion resistance of concrete by 50% or more compared to air drying without the use of curing materials or the use of poor quality curing materials. The effect of curing becomes more pronounced with the severity of the atmospheric conditions.

2. Effective curing methods used for sufficiently long durations can significantly reduce drying shrinkage cracking by reducing both the rate and magnitude of shrinkage at a given early age.

3. The corrosion potential of steel in concrete that is subjected to surface applied chlorides is significantly affected by how well the concrete is cured because the permeability of the concrete surface to chlorides is greatly influenced by the curing. The time to the start of corrosion activity as well as the rate of corrosion are significantly affected. Everything else being equal, by curing concrete properly it is possible to increase the service life of a structure through the control of the corrosion of the steel in the concrete.

4. The effect of curing on the development of the pore structure of cement paste has been shown clearly with the absorptivity approach. The capillary porosity of the surface region of concrete can be reduced by as much as 80% or more (depending on the ambient conditions) by curing the concrete properly. This has a significant impact on corrosion and scaling potential.

5. Taking the necessary steps to promote proper curing of concrete should be an indispensable part of the construction process if the concrete is to achieve its full potential. This includes selecting effective curing methods and materials since the effectiveness of curing materials, particularly curing compounds, varies a great deal."

3.8 **Whiting, D., DURABILITY OF HIGH-STRENGTH CONCRETE, Concrete Durability, Katharine and Bryant Mather International Conference, SP-100, American Concrete Institute, 1987, pp. 169-186.**

"Concrete mixtures were designed to nominal 28-day compressive strengths of 41, 55, and 69 MPa (6,000, 8,000, and 10,000 psi) using mix designs typical of commercial production of high strength concretes."

Concrete specimens were produced using moist curing as well as moist curing followed by air curing.

"Air curing had generally beneficial effects on resistance to freezing and thawing and application of deicing agents to normal strength, air-entrained concretes, but had little positive influence on durability of high strength mixtures."

"The objective of this study was to develop information on the durability of high strength concretes under conditions of freezing and thawing and application of deicing agents. The information developed could be used to make recommendations on the minimum air content needed for durability of high strength concrete under various conditions of curing and exposure. The objectives were carried out under the following scope:

1. Concretes were prepared at nominal strength levels of 41 MPa (6,000 psi), 55 MPa (8,000 psi) and 69 MPa (10,000 psi). Air contents were selected in the ranges of non-air entrained, 3 to 4% , 4 to 6% , and 7 to 9% , by volume of concrete.

2. Concretes were given two types of curing, These were (a) a 28-day moist cure and (b) a cure consisting of 7-days moist followed by 21 days of air drying. Cure b was applied only to the 41 MPa (6,000 psi) and 69 MPa (10,000 psi) concretes.

3. Specimens were tested for resistance to freezing and thawing...and resistance to deicer scaling...."

"Performance of non-air entrained concretes in this study was poor, irrespective of strength level or type of curing."

The cement used in these studies was an ASTM Type I that has been successfully used on projects in Chicago, Illinois, involving high strength concrete construction.

"Specimens were stripped from their molds the day following casting and placed in a moist room maintained at 23±1.5 °C (73±3 °F) and 100% relative humidity (condensing) for the selected period of cure."

The author's conclusions are as follows:

- "Regardless of strength level or type of curing, performance of non-air entrained concretes with respect to resistance to freezing and thawing and deicer scaling is poor.

- The air-entrained concretes produced in this study performed well when exposed to freezing and thawing while continuously submerged in tapwater, even at air contents in the range of 3 to 4 percent measured in the plastic concrete. Scaling induced by this freezing was less in the higher strength concretes.

- Air-entrained, high strength concretes showed less resistance to deicer scaling than concretes of more moderate strength levels produced at equivalent air contents.

- Air curing had a beneficial effect on improving durability of concretes of moderate strength levels with respect to both freezing and thawing in water and application of deicing agents. Air curing had less of an effect on durability of high strength concrete."

3.9 **Schönlin, K. and Hilsdorf, H., EVALUATION OF THE EFFECTIVENESS OF CURING OF CONCRETE STRUCTURES, Concrete Durability, Katharine and Bryant Mather International Conference, SP-100, American Concrete Institute, 1987, pp. 207-226.**

The synopsis for this article states: "For the evaluation of the effectiveness of curing of concrete in the field a non-destructive, rapid test method has been developed. With this method air permeability of concrete surface layers is measured within a period of about 10 minutes, expressed in terms of a permeability index.

Laboratory experiments show a close correlation between the measured permeability index and the duration of curing, curing temperature, type of cement, w/c-ratio and content of fly ash of the concrete. The method is very sensitive to changes in most parameters which affect the pore structure of the hydrated cement paste and thus the durability of concrete structures under normal exposure conditions."

Inadequate curing practices are the primary cause of durability problems with concrete in many parts of the world. In the field, the durability of concrete is largely determined by the properties of the surface layers, and these properties depend on the curing effectiveness.

"Air permeability of the surface region of a concrete member is influenced by the porosity as well as by the pore size distribution of the hydrated paste."

"Since the thickness of the surface layer through which air flow occurs is unknown or at least not well defined the permeability of the concrete surface layer is described in terms of the permeability index M.

$M = Q / \Delta h$

where M $=$ permeability index [m^2/sec]

Q $=$ rate of flow [m^3/sec]

Δh $=$ pressure difference of air in the vacuum chamber and the atmosphere [mbar]"

An experimental program determined the permeability index for different types of concrete exposed to various curing conditions. "The parameters studied were duration of curing, curing temperature, type of cement, w/c-ratio and fly ash content." Permeability decreases with increasing duration of curing.

The authors report the following conclusions:

- "A test apparatus was developed which allows an estimate of curing of concrete on the basis of a permeability index as a measure of the air permeability of a concrete surface layer.

- The test method is non-destructive, applicable under site conditions and gives results within approximately 10 minutes.

- Experiments carried out with different concretes showed that the test method confirms the well-known behaviour [sic] of concrete relative to duration of curing, curing temperature, and type of cement and w/c-ratio.

- The permeability indices measured vary by several orders of magnitude depending on the properties of the surface layer of the concretes and thus distinguishes very well between 'good' and 'bad' concrete surfaces.

- There appears to be a limiting value of the permeability index which cannot be reduced significantly by further curing. This value was similar for all concretes examined and is about 10 to 30 x 10^{-11} m^2/sec."

3.10 Carrasquillo, P. M. and Carrasquillo, R. L., EVALUATION OF THE USE OF CURRENT CONCRETE PRACTICE IN THE PRODUCTION OF HIGH-STRENGTH CONCRETE, ACI Materials Journal, Vol. 85, No. 1, January-February 1988, pp. 49-54.

"A research program was conducted for the study of various quality-control procedures as applied to high-strength concrete. Over 1000 specimens for strength evaluation were cast from 29 high-strength concrete mixtures having compressive strengths ranging from 41.4 MPa to 100 MPa (6,000 to 14,500 psi) at 28 days. Variables investigated included test specimen size, cylinder mold material, curing conditions, addition of superplasticizer, and cylinder capping method."

Concrete specifications and quality-control procedures as currently written and used may not be applicable to high-strength concrete.

"The effects of three different curing conditions on both the flexural and compressive strength of high-strength concrete were investigated. The first condition was standard moist curing at 100% relative humidity and a temperature of 23 ± 1.7 °C (73.4 ± 3 °F). For the second condition, the specimens were coated with a curing compound upon demolding at 24 hr, and then stored under ambient conditions. For the third curing condition, the specimens were demolded at 24 hr, and stored under ambient conditions without application of a curing compound. For the period of these tests, ambient temperatures were between 27 and 38 °C (80 and 100 °F), and the relative humidity was between 30 and 60 percent. The second and third curing conditions were used in an effort to simulate field-curing conditions and to determine how specimens cured under these conditions compared to those given ideal moist curing."

Results were "...cylinders cured under ambient conditions and treated with a curing compound tested slightly higher than standard-cured cylinders at ages up to 15 days. However, when tested at 28 days, cylinders receiving standard moist curing yielded approximately equal results with those stored under ambient conditions either with or without a curing compound.... At test ages of 56 to 91 days,...the compressive strength of standard moist-cured cylinders surpassed that of cylinders stored under ambient conditions and treated with a curing compound."

"The effect of curing conditions on the flexural strength of high-strength concrete is much more pronounced than on the cylinder compressive strength.... Field-cured beams treated with curing compound and stored under ambient conditions tested, on average, at 58 percent of beams moist cured until testing for test ages of 3, 7, and 28 days.

The higher compressive strength at early ages of cylinders treated with curing compound could be attributed to accelerated hydration due to storage at higher temperatures than the ideal moist curing temperature of 23 ± 1.7 °C (73.4 ± 3 °F). However, by 28 days, the effect of drying and accelerated curing of the specimens is reflected in decreased strength when compared to standard moist-cured specimens. The significant difference in flexural strength between high-strength concrete beams that are moist cured and field cured can be attributed in part to drying of the surface of the concrete specimens coated with the curing compound. This drying induces an initial tensile stress at the surface, thus resulting in lower apparent strengths at failure."

"Both the compressive and flexural strengths of high-strength concrete specimens are lower when cured under field conditions than when given standard moist curing."

3.11 **Senbetta, Ephraim, CONCRETE CURING PRACTICES IN THE UNITED STATES, Concrete International, Vol. 10, No. 11, November 1988, pp. 64-67.**

This article summarizes the results of a survey sent to all 50 state highway departments to obtain information about their concrete-curing practices.

"The most commonly used method of curing concrete pavements, bridge decks, and other structures under the jurisdiction of the state highway departments is application of membrane-forming curing compounds."

"The most commonly specified durations of curing are three days minimum and seven days maximum."

Major conclusions from the survey are:

- "Specifying a minimum coverage rate is used by almost all the states as the primary means of insuring good curing. However, only eight percent of the states take into consideration surface texture of the concrete when specifying coverage rates."

- "The minimum curing period specified by most states (three days) seems to be too short, especially for bridge decks."

The author emphasizes "...there is a clear need for educational programs designed to increase the awareness of practitioners about the virtues of curing concrete and the consequences of neglecting it."

3.12 **Bentur, Arnon and Goldman, Ariel, CURING EFFECTS, STRENGTH AND PHYSICAL PROPERTIES OF HIGH STRENGTH SILICA FUME CONCRETES, Journal of Materials in Civil Engineering, Vol. 1, No. 2, May 1989, pp. 46-58.**

"The physical properties of high strength silica fume [SF] concretes and their sensitivity to curing procedures were evaluated and compared with reference portland cement concretes, having either the same concrete content as the silica fume concrete or the same water to cementitious materials ratio. [...] The effects of poor curing procedures on the strength, and the skin properties, were found to be equally detrimental in the reference and in the silica fume concretes."

"Since many of the high strength concretes are formulated by using pozzolans, and the silica fume might be included in this category, there is always the concern to what extent are these concretes more sensitive to the water curing procedures than concretes prepared with portland cement only. This is particularly important in hot-dry climatic conditions, where the concrete is dried more readily, thus perhaps eliminating the moisture that is needed for the progress of the pozzolanic reaction which can continue to occur beyond the initial few days of the water curing period. In evaluating the effect of curing, one should consider the overall strength of the concrete, as well as the properties of the concrete skin..., which protects the steel reinforcement. Since drying is not uniform and occurs more readily in the skin, there may be enough moisture in the core of the concrete to facilitate reasonable strength generation, but the ≈25 mm (1 in) thick skin may not develop the dense microstructure obtained in the core."

The objective of this study was "...to characterize high strength silica fume concretes from the points of view of heat generation, shrinkage and sensitivity to curing, and to compare their performance with that of concretes made of portland cement only, having either the same cement content or the same water to cementitious materials ratio."

Tests were carried out to determine:
"(1) The heat evolution in adiabatic conditions;
(2) the shrinkage of mature concretes; and
(3) the effect of curing on the strength and on the properties of the skin."

Curing methods:
"The effect of limited water curing was evaluated in two different environmental conditions, one of which might be considered as mild (20 °C/60% RH) (68 °F/60% RH) and the other as harsh (30 °C/40% RH) (86 °F/40% RH). The water treatment in the mild conditions included 7 days curing in water, followed by exposure to 20 °C/60% RH (68 °F/60% RH) until the age of test. For comparison, companion concrete specimens were kept continuously in water until testing."

"The water curing procedure in the 30 °C/40% RH (86 °F/40% RH) conditions was intended to simulate a field practice in which the concrete is sprayed twice a day with water and then exposed to the hot-dry conditions. This was achieved by immersing the concrete specimens in water for 5 minutes, twice a day, and then exposing to 30 °C/40% RH (86 °F/40% RH). This water treatment was carried out for 1, 2, 3 or 6 days, immediately after demolding. [...] For comparison to a proper water curing procedure, companion specimens were subjected to a 6 day continuous water immersion (after being sealed in the molds for the first day) and then exposed to 30 °C/40% RH (86 °F/40% RH)."

Effect of Curing:
In the silica fume concretes, "...the air curing was not detrimental to strength. This might be attributed to the observations that the strengthening influence of the silica fume takes place quite early, during the period 1 to 28 days..., in contrast to later age effects in conventional pozzolans, and the possibly slower rate of drying from within the silica fume concrete, which can apparently develop a tight microstructure after 7 days of water curing."

"...results suggest that even for poor curing procedure, there is no significant difference between the reference and the SF concretes with respect to increase in the depth of carbonation."

"...for 3 to 6 days of intermittent spray curing, the reduction in strength was about 20%, whereas the increase in depth of carbonation was about 100%. This suggests that in these systems, regardless of the composition of their cementitious material, the adverse effect of limited water curing is of greater consequence to the properties of the concrete skin (represented by the depth of carbonation) than to the compressive strength of the bulk concrete."

Conclusions:

1. "The presence of SF resulted in a marked increase in strength, especially at 28 days, but also at 1 day."

2. There is "...an accelerating effect of the SF on the reaction of the portland cement, and this may account for the relatively high strength achieved at one day, although the pozzolanic reaction is probably not very effective at this stage."

3. "The presence of SF reduced the shrinkage strains considerably, and this was accounted for by the much lower rate of weight loss in this system, due probably to its much finer pore structure."

4. "The effects of poor curing procedures on the strength and skin properties of concretes were found to be equally detrimental in the reference and in the SF concretes."

3.13 Asselanis, Jon G., Aitcin, Pierre-Claude, and Mehta, P. K., EFFECT OF CURING CONDITIONS ON THE COMPRESSIVE STRENGTH AND ELASTIC MODULUS OF VERY HIGH-STRENGTH CONCRETE, Cement, Concrete, and Aggregates, Technical Note, Vol. 11, Summer 1989, pp. 80-83.

"Since freshly made concrete is very permeable and can rapidly lose moisture to the environment, the importance of moist curing is well emphasized in both laboratory and field practice. To achieve adequate levels of strength and durability, it is generally recommended that ordinary concrete be moist cured for periods ranging from 7 to 28 days."

"High-strength concrete mixtures contain relatively high cement content, a superplasticizing mixture, and very low water content...." Normally about 0.3 water-cement ratio is used. "Such mixtures can achieve a discontinuous pore structure and low permeability within a few days of cement hydration. The need for prolonged moist curing to obtain the desired levels of strength and imperviousness, which is well established with ordinary concrete mixtures, is therefore questionable in the case of high-strength concrete. The purpose of the laboratory study reported here was to evaluate the influence of curing conditions on the properties of high-strength concrete. Compressive strength, elastic modulus, and stress-strain behavior were among the properties investigated."

Portland cement Type II with a water-cement ratio of 0.31 was used. The mixture contained both silica fume and a superplasticizer. Compressive strengths obtained at 28 days ranged from 81.2 MPa (11,780 psi) for air cured specimens to 99.2 MPa (14,390 psi) for 7 days moist cured followed by 14 days air cured.

"With a given aggregate type, generally there is a direct relationship between compressive strength and elastic modulus." Results show that "...the elastic modulus data [from this study] confirm the general conclusions drawn...[concerning] the influence of curing conditions on compressive strength of the high-strength concrete. For instance, specimens moist cured for only 1 d...showed significantly lower strengths and elastic moduli than specimens moist cured for 7 d or more and subsequently air cured...."

Test results confirmed "...that with high-strength concrete a prolonged period of moist curing beyond the initial 7 d is not needed for improvement of mechanical properties of concrete."

Results from stress-strain tests indicate that stress relaxation time is increased by dry curing.

With respect to weight changes, tests showed "...that 1 d moist curing in molds did not make the concrete impervious enough to prevent substantial moisture loss." However, "... concretes moist cured for 7 days appear to have acquired sufficient imperviousness."

The authors had the following conclusions:

"Based on the results of experimental work with a high-strength concrete mixture (0.3 water/cement ratio), it is concluded that a 7-d moist-curing period is sufficient to make the concrete sufficiently impervious. Further moist curing beyond this period was not needed to substantially enhance the compressive strength and elastic modulus of concrete. Curing in air after the initial 7-d moist curing caused considerable improvement in engineering properties. This is because the concrete, having become impervious, retained enough moisture needed for cement hydration. The weight changes data under different curing conditions generally support the conclusions."

3.14 Collins, Therese M., PROPORTIONING HIGH-STRENGTH CONCRETE TO CONTROL CREEP AND SHRINKAGE, ACI Materials Journal, Vol. 86, No. 6, November-December 1989, pp. 576-580.

"The results of the test program reported in this article showed that creep and shrinkage deformations are somewhat less for concrete mixtures with lower paste contents and larger aggregate size."

"Concrete creep is influenced by mixture proportions, type of aggregate, and age at loading. Concrete shrinkage is directly related to water-cement ratio, mixture proportions, type of aggregate, and curing conditions." There is not much information available on the creep characteristics of high strength concrete.

"An experimental investigation was conducted on high-strength concrete produced in the St. Paul-Minneapolis area. The test program consisted of preparing five concrete mix designs and documenting the strength, modulus of elasticity, creep, and shrinkage characteristics."

The Type I portland cement was used. The water-cementitious materials (cement plus fly ash) ratio had a target value of 0.36.

Conclusions:

- "The shrinkage deformation is inversely proportional to the moist-curing time. The longer the moist-curing time, the lower the shrinkage deformation."
- "The creep deformation increases directly with an increase in the applied stress level."
- Test results from this study indicate that concrete mixtures that contain a large maximum aggregate size {38.1 mm (1 ½ in)} along with a low paste content will provide more desirable creep and shrinkage characteristics.
- "The use of a high-range water-reducing admixture did not have a significant effect on the creep and shrinkage deformations."
- "By lowering the paste content and maximizing the coarse aggregate, a high-strength concrete can be produced with a modest improvement in creep and shrinkage deformations. However, the reduction in stress level has a much more significant effect on the resulting creep and shrinkage strains. To lower the stress level, a concrete facility should explore the highest strength, most dense concrete possible."

NOTE: Items numbered 3.15 through 3.22 below are from: **Proceedings, Third International Conference, Fly Ash, Silica Fume, Slag, And Natural Pozzolans In Concrete,** Trondheim, Norway, 1989, ACI SP-114, American Concrete Institute

3.15 **Roy, D. M., FLY ASH AND SILICA FUME CHEMISTRY AND HYDRATION, Vol. 1, pp. 117-138.**

"This paper discusses the chemistry and hydration reactions of silica fume (SF) and fly ash (FA) blends in a general sense."

"The hydration of cement is relatively complex and becomes additionally so when supplementary cementing materials are added."

"Hardened cement paste has a finely intergrown microstructure dominated by the major binding component, the very fine high surface area intergrowth of calcium silicate hydrate (C-S-H)."

"When fly ash or silica fume are added, the hydration process is affected substantially, reflecting the modified chemical composition, reactivity of the components, their particle size, size distribution, shape, and other factors which affect the final paste structure and its performance as the matrix of concrete. The utilization of...FA and...SF therefore presents challenges and opportunities; their addition to the concrete mixture affects both the hydration process and the characteristics of the hardened concrete."

"The hydration reactions in cement pastes incorporating fly ash and silica fume are responsible for the microstructural development. These complex reactions involve phase solubility, accelerating and retarding effects of a multiphase, multi-particle material, and surface effects at the solid-liquid interface. The initial degree of dispersion of cement and blending agents in the paste strongly influences the development of final hardened paste microstructure. Surface charge, as measured by the zeta-potential at the solid-liquid interface...reflects the dispersion of the system. The floc structure of fresh cement paste affects its workability, and the incorporation of ash affects the floc structure, generally interrupting the structure, creating smaller units, thereby imparting greater fluidity. Adequately dispersed silica fume can provide a similar effect and also, due to its ultra-fine particle size, fill the intergranular interstices and produce a denser paste structure, reflected in very high strength."

"Both physical and chemical characteristics influence the hydration kinetics of each of the blended cement materials in a specific manner. Silica fume ordinarily accelerates the early portland cement hydration, largely because of its very high surface area, accelerating and increasing the heat development resembling a high early strength cement. Fume also disperses the hydration product, provides for deposition of C-S-H, and thereby fills the pore interstices with fine hydration products. Its optimal use is with superplasticizers to minimize the water demand and adequately disperse the fine particles. Dense products with fine pore size, very low permeability, and low ionic diffusivity commonly are the result. Despite the rapid early hydration, much silica fume remains unreacted until a later stage."

3.16 **Killoh, D. C., Parrott, L. J., and Patel, R. G., INFLUENCE OF CURING AT DIFFERENT RELATIVE HUMIDITIES ON THE HYDRATION AND POROSITY OF A PORTLAND/FLY ASH CEMENT PASTE, Vol. 1, pp. 157-167.**

Paste specimens (8 mm thick) were made with a water-binder (ordinary portland cement + pulverized fly ash) of 0.59 and were cured under saturated conditions for 7 days. The specimens were then stored in containers at relative humidities (r.h.) ranging from 12 to 100%. At ages of 7, 28, and 91 days the degree of hydration and porosities were measured.

"The strength and durability of concrete depend largely on the extent to which the hydrates produced fill the space originally occupied by water, and on the effectiveness of these hydrates in producing a dense low permeability matrix. Whereas strength is a bulk property of the concrete, durability is controlled in the main by the surface layers. High porosity in the surface will allow the ingress of deleterious agents which may cause durability problems. Drying of the concrete, particularly at early ages, caused by a poor curing regime leads to restricted hydration in the surface layers and thus to higher porosities and permeabilities."

Data from this paper shows "...that very little further hydration occurs after 7 days curing if the relative humidity is then held below 70%.... Above 70% r.h. hydration increases almost linearly up to saturated curing. Both the hydration and the pozzolanic reaction appear to be affected similarly by a reduced curing relative humidity; below 70% r.h. reaction virtually ceases."

"The fact that large diameter porosity only decreases above 95% r.h. has some very important implications. The permeability of a concrete is largely controlled by the volume of large pores and their connectivity. Whilst nothing can be said from this data about pore connectivity it is clear that high moisture contents are essential to obtain a minimum large diameter porosity."

"An exposure relative humidity of less than 95% for a significant period is likely to cause a very significant increase in the permeability of a concrete. Whilst this may occur when curing has been completed, it is evident that prolonged moist curing at early ages will ensure, particularly for OPC/pfa concrete, a low large diameter porosity, a high diffusion resistance and hence good durability."

"Total porosity is little affected by the curing relative humidity after the initial 7 day moist curing period, decreasing only a very small amount even under saturated condition up to 90 days."

3.17 **Ronne, M., EFFECT OF CONDENSED SILICA FUME AND FLY ASH ON COMPRESSIVE STRENGTH DEVELOPMENT OF CONCRETE, Vol. 1, pp. 175-189.**

This paper reports on an investigation among three laboratories of the effect of various curing conditions on the long-term (up to 2 years) compressive strength (cube) of normal strength concrete made with additions of fly ash and silica fume plus fly ash. Six curing conditions were used:

- Cured under water at 20 °C from the time of demolding until testing.

- Cured in air at 20 °C and 50% r.h. from time of demolding until testing.
- Cured under water at 20 °C for 3 days and then cured in air at 50 % r.h. until testing.
- Stored in plastic molds exposed to air at 50% r.h. to simulate drying from one face.
- Cured under water for 28 days at 20 °C then cured under water at 70 °C.
- Cured in air at 20 °C and 50% r.h. for 28 days then exposed to air at 70 °C.

"Good initial curing conditions in the first three days of curing gave an improvement in compressive strength compared to the samples dried immediately after demolding."

Concrete with condensed silica fume proved to be more sensitive to drying than concrete without it.

3.18 Thomas, M. D. A., Matthews, J. D., and Haynes, C. A., THE EFFECT OF CURING ON THE STRENGTH AND PERMEABILITY OF PFA CONCRETE, Vol. 1, pp. 191-217.

"Tests were carried out on a series of concrete mixes, designed to equal workability and 28-day compressive strength and with a range of pfa [pulverized-fuel ash] levels, in order to study the effect of curing on the strength and permeability of pfa concrete. [...] The results confirm the importance of curing, with reductions in curing period resulting in lower strength, more permeable concrete. The strength of the pfa concretes appears to be more sensitive to poor curing than the opc [ordinary portland cement] concrete, the sensitivity increasing with increasing pfa content."

"Adequate curing is essential for all concrete, whether or not it contains pulverised [sic]-fuel ash (pfa), if the potential properties of the concrete are to be fully realized. However, since the long-term benefits associated with the pozzolanic reaction are more evident in well cured concrete, it has generally been considered that pfa concrete has a greater susceptibility to poor curing than opc concrete." It has been "...confirmed that the compressive strength of pfa concrete is more adversely affected by inadequate curing when compared with opc concrete but studies on the relative effects of curing on concrete durability have drawn varied conclusions especially with respect to rate of carbonation."

The study reported in this article looks at the response of the strength and permeability of opc and pfa concrete to a variety of different curing conditions.

"All specimens remained in their moulds [sic] under damp hessian and polythene and at 20 °C (68 °F) until they were demoulded [sic] at 24 hours. Concrete specimens were then given one of the following treatments:

(i) 1 day cure - i.e., air-stored immediately after demoulding [sic].

(ii) 2 days cure - kept under damp hessian and polythene for a further 1 day prior to air-storage (cubes only).

(iii) 3 days cure - kept under damp hessian and polythene for a further 2 days prior to air-storage.

(iv) 7 days cure - kept under damp hessian and polythene for a further 6 days prior to air-storage.

(v) Water-stored - immersed in water until test."

"The long-term strength of all the concretes tested was significantly decreased by reducing the curing period. None of the concretes initially cured for one or two days achieved 90-day strengths in excess of their 28 day water-cured strength."

"The [oxygen] permeability of all the concretes was decreased by extending the curing period, those cured for only 24 hours being on average about three times as permeable as those cured for 7 days."

"The [water] permeability of all the concretes was significantly decreased by extending the period of curing, those receiving only one day's curing being as much as 210 times more permeable than the same concrete cured for 7 days."

With respect to both oxygen and water, permeability decreased with increasing duration of curing and, generally, pfa content.

The importance of providing adequate curing for all concrete cannot be over-emphasized when considering the permeability of the surface layer.

Conclusions:

1. "The effects of curtailing the period of initial curing of opc and pfa concretes designed to equal strength grade were to retard the rate of strength development, decrease the maximum compressive strength and increase the permeability of the concretes to oxygen and water.

2. Under the worst conditions of curing the pfa concretes recorded lower compressive strengths than the control but were, generally, less permeable."

3. Recommendations for minimum periods of moist-curing and protection for concrete are 2 days for opc concrete and 2.7 (or 3) days for pfa concrete. Indications are "...that this longer curing period is required for pfa concrete to achieve strength parity with opc concrete and may need to be further extended in the case of high pfa contents or where strength parity is required at early ages. However, an extended period of curing is not necessary in order for pfa concrete to achieve lower permeability than opc concrete."

4. It is thought "...that for similarly-cured concretes of equal grade, pfa concrete with pfa contents up to 30% will provide protection to steel reinforcement at least equal to that of opc concrete."

3.19 **Barrow, R. S., Hadchiti, K. M., Carrasquillo, P. M., and Carrasquillo, R. L., TEMPERATURE RISE AND DURABILITY OF CONCRETE CONTAINING FLY ASH, Vol. 1, pp. 331-347.**

Specimens of concrete made with fly ash were exposed to six different curing conditions after removal from their molds at 24 hours. Curing was performed at temperatures of 11.3, 25.6, or 42.5 °C and at relative humidities of 50 or 100 %. Temperature rise, abrasion resistance, and resistance to deicer scaling were measured.

It is known "...that concrete containing fly ash is especially sensitive to curing conditions. Thus, properties of concrete containing fly ash which would be expected to be affected most heavily by differences in curing conditions would be those properties which depend on the condition of an exposed surface, such as abrasion resistance and resistance to deicer scaling."

"The most important factor affecting the abrasion resistance of concrete was found to be its compressive strength at the time of testing. The various curing environments of the test specimens played a primary role in the strength development of the concrete tested. For the moist cured specimens containing fly ash, an increase in curing temperature was generally accompanied by an increase in compressive strength. For the specimens containing fly ash and cured at 50% relative humidity, the compressive strength was generally lower than that of specimens moist cured at the same temperature."

The authors state that "...since the compressive strength of concrete containing fly ash may be affected more detrimentally by improper curing than that of concrete containing no fly ash, the abrasion resistance of concrete containing fly ash may, as a result, be less."

"Due to the strong dependence of the abrasion resistance of the concrete on its compressive strength, and to the sensitivity of concrete containing fly ash to curing conditions, it is recommended that special precautions be taken to ensure the adequate curing of concrete containing fly ash."

3.20 **Holland, T. C., WORKING WITH SILICA FUME IN READY-MIXED CONCRETE—U. S. A. EXPERIENCE, Vol. 2, pp. 763-781.**

"The first silica fume admixture aimed at the ready-mixed market appeared in the United States in 1983. Since then, the use of silica fume has developed slowly. It is currently being used as a cement replacement material or as a performance-enhancing admixture."

"In 1983 the first large scale project using silica-fume concrete was completed in the

United States." Silica fume was used to obtain a very high compressive strength to increase the abrasion resistance of the concrete.

"The use of silica fume to achieve either high strength or low permeability has been the primary application of the material...in the United States."

"In a few limited areas in the United States, silica fume is also currently being used as a portland cement replacement material."

"Silica-fume concrete will not perform well unless it is properly cured, and proper curing is particularly important for concretes containing high dosages of silica fume in conjunction with low water contents. The general recommendation for curing has been to 'over cure' the concrete. Over curing has been emphasized to mean that to get the maximum benefit from silica fume, more curing than would be done for conventional concrete in the same placement should be done. As might be expected, this recommendation has not always met with overwhelmingly positive response from contractors.

Silica-fume concrete has been successfully cured using most of the generally accepted practices -- wet burlap, sheets of plastic, and curing compound. As an absolute minimum, curing equivalent to 7 days of wet curing has been recommended.

Curing of silica-fume concrete can usually begin immediately after finishing, whatever the finishing process may be. Since high dosages of silica fume produce concrete that does not bleed, there is no requirement to wait for the concrete to set so that the bleeding will stop before initiating curing. On projects where finishing after setting was not required, curing compound has been applied within a few minutes of the pass of a vibrating screed."

With respect to concrete subjected to accelerated curing, the author says: "Problems relating to strength gain have been reported in some precast operations. The problem has usually been traced to the chemical admixtures incorporated in a silica fume product rather than the silica fume itself. Since these chemical admixtures frequently include retarders, it has been necessary to modify the curing cycle. After the silica-fume concrete was allowed to reach an initial set before beginning the accelerated curing, strength problems were resolved."

3.21 **Marusin, S. L., INFLUENCE OF LENGTH OF MOIST CURING TIME ON WEIGHT CHANGE BEHAVIOR AND CHLORIDE ION PERMEABILITY OF CONCRETE CONTAINING SILICA FUME, Vol. 2, pp. 929-944.**

"The purpose of this research was to study the influence of the length of moist curing time on weight change behavior, chloride ion content and chloride ion distribution profile through 10 cm (3.94 in) concrete cubes made from concretes containing silica fume (SF). Three concretes containing 2.5, 5 and 10 percent silica fume by weight of cement, respectively, were prepared and tested. The concrete cubes were moist cured 1, 3, 7 and 21 days. Then, after 21 days of air-drying all the cubes were immersed in 15 percent NaCl solution for 21 days. Following the 21-day soaking period and a subsequent 21-day final air-drying period, chloride ion contents at four different depths were determined using a potentiometric titration procedure.

The test results showed that weight gain rate and chloride ion penetration in all tested concretes decreased when the length of moist curing period increased. All tested concretes showed the best performance...after the maximum moist curing period of 21 days used in this study."

"Water absorption, water vapor transmission and penetration of chloride ion content into the concrete containing SF are greatly influenced by the length of moist curing period. The lowest weight gain in salt solution and the lowest chloride ion content were achieved with concrete cured for the maximum moist curing period of 21 days."

3.22 **Langlois, M., Beaupre, D., Pigeon, M., and Foy, C., THE INFLUENCE OF CURING ON THE SALT SCALING RESISTANCE OF CONCRETE WITH AND WITHOUT SILICA FUME, Vol. 2, pp. 971-989.**

"Test results...indicate the importance of curing on the de-icer salt scaling resistance of concrete. Concretes cured with a curing compound can have an excellent scaling resistance (as good as that of concretes moist cured for 14 days), but the results seem to vary with each type of compound used. It cannot therefore be concluded that all curing compounds will have such a positive influence. Accelerated heat curing can have an extremely negative influence and its use cannot be recommended for concretes that will be exposed to de-icer salts.

The effect of silica fume on the salt scaling resistance of concrete (at least as regards moulded [sic] surfaces) does not seem to be positive, but further research is necessary in order to draw more complete conclusions."

4. LITERATURE FROM 1990 TO 1995

4.1 Haque, M. N. , SOME CONCRETES NEED 7 DAYS INITIAL CURING, Concrete International, Vol. 12, No. 2, February 1990, pp. 42-46.

"Proper curing is essential for strength development and durability of concrete. Most codes of practice recommend sufficient curing to achieve a maturity equivalent to seven days moist curing, especially when the exposure conditions are likely to be severe."

Studies were "...undertaken to evaluate the strength development and durability of the concrete system in warm-dry {45 °C (113 °F) at 20 percent RH} and temperate-dry {23 °C (73 °F) at 40 percent RH} conditions focused on the characterisation [sic] of cement pastes with and without fly ash. The results established that, given adequate prior moist curing of 7 days, the strength and strength development characteristics of the cement-fly ash paste was superior to plain cement paste in both warm-dry and temperate-dry conditions."

"Lack of any moist curing adversely affects the compressive strength of both plain and fly ash concrete at all ages...."

"As the concrete ages [beyond 7 days] the detrimental effect of lack of fog curing becomes more pronounced, the strength ratios dropping to between 59 and 80 percent at 28 days and between 44 and 70 percent at 91 days. Fly ash concrete is affected the most, having average strength ratios of 65 percent at 28 days and 49 percent at 91 days. The corresponding figures for plain concrete are 77 percent and 68 percent." The strength ratio refers to the ratio of average compressive strength between fog-cured specimens and specimens exposed to temperate-dry and warm-dry conditions.

The author concludes that "...fog curing for at least 7 days is more important when concrete containing fly ash will be exposed to drying ambient conditions."

4.2 Maage, Magne, Smeplass, Sverre, and Johansen, Randulf, LONG TERM STRENGTH OF HIGH STRENGTH SILICA FUME CONCRETE, Utilization of High-Strength Concrete, Second International Symposium, Berkeley, California, May 1990, 14 pp.

"Use of silica fume is important to produce high strength concrete. Possible effects on long term properties are therefore of vital interest for the future development of high strength concrete.

It has been reported that silica fume concrete stored in air showed strength loss from 90 days to 5 years, but reasons are not discussed. The report was based on a limited number of results. Similar results are not found in up to ten years old high strength concrete in Norway neither in laboratory tests nor by testing samples from existing structures.

Results from two major research projects showed that for laboratory stored specimens, the strength increased or was constant for concrete stored in water or air, respectively. No difference was found between high and normal strength concretes. The increase was somewhat higher for concretes without silica fume compared to concretes with up to 20 % silica fume by weight of cement. Furthermore, the strength increase was somewhat higher for water stored concretes than for air stored. However, high strength silica fume concrete was not more sensitive to early drying than concrete without silica fume.

High strength concrete from several existing structures did not exhibit the same, consistent pattern in strength development, however. This is probably due to insufficient documentation at an early age. However, the results did not show any significant negative long term strength development."

4.3 Carino, Nicholas J. and Clifton, James R., OUTLINE OF A NATIONAL PLAN ON HIGH-PERFORMANCE CONCRETE: REPORT ON THE NIST/ACI WORKSHOP, MAY 16-18, 1990, NISTIR 4465, December 1990.

Several definitions of high-performance concrete (HPC) being discussed in 1990 are given:

Strategic Highway Research Program (SHRP) definition of HPC:

- It shall have one of the following strength characteristics:
    1. 28-day compressive strength greater than or equal to 70 MPa (10,000 psi), or
    2. 4-hour compressive strength greater than or equal to 20 MPa (3,000 psi), or
    3. 24-hour compressive strength greater than or equal to 35 MPa (5,000 psi)
- It shall have a durability factor >80% after 300 cycles of freezing and thawing.
- It shall have a water-cementitious materials ratio less than or equal to 0.35.

The definition used at the NIST/ACI Workshop:
"Concrete having desired properties and uniformity which cannot be obtained routinely using only traditional constituents and normal mixing, placing, and curing practices. As examples, these properties may include:

- Ease of placement and compaction without segregation
- Enhanced long-term mechanical properties
- High early-age strength
- High toughness
- Volume stability
- Long life in severe environments"

Area requiring research for wider use of HPC: "Curing of low w/c [water-cement ratio] HPC (and development of recommended practices)."

The following research needs were identified in the general area of curing HPC:

- "Evaluate effectiveness of moist curing considering the completeness of hydration as a function of time."

"HPC will typically have very low permeability which may restrict the inward movement of moisture, thereby, impeding the hydration of the inner core of concrete elements made with low water-cement ratios. Information is needed on the effectiveness of moist curing to determine if new curing practices should be developed."

- "Seek an understanding of interactions between ambient exposure conditions, mix rheology, and needed evaporation control measures."

"HPC usually does not exhibit bleeding and thus surface drying cracking can develop if the evaporation of moisture is not curtailed. Information is needed on the effectiveness of methods for controlling evaporation, such as fogging and evaporation retardants. The effects of the methods on the quality of the near-surface hardened cement paste should be investigated by considering the resulting surface w/c ratio, durability (e. g., abrasion resistance), and permeability."

- "Develop a more comprehensive understanding of the effects of internal curing temperatures on HPC, and develop guidelines for curing HPC based on sound technical knowledge."

"HPC will usually have higher cement contents than normal concrete, and thus higher internal temperatures. The effects of higher internal temperatures on microstructure (e. g. microcracks) and strength need to be determined."

- "Develop methods to determine degree of curing of HPC."

"The cement in HPC will not hydrate to the same extent as that in conventional concrete. The properties of HPC may be more sensitive to degree of curing than conventional concrete. Therefore, methods are needed to reliably determine the degree of curing of HPC."

"The maturity concept has proven to be a convenient tool for monitoring strength gain during the curing of conventional concrete. The applicability of the maturity concept to HPC mixtures needs to be investigated."

4.4 **Kijellsen, Knut O., Detwiler, Rachel J., and Gjorv, Odd E., DEVELOPMENT OF MICROSTRUCTURES IN PLAIN CEMENT PASTES HYDRATED AT DIFFERENT TEMPERATURES, Cement and Concrete Research, Vol. 21, No. 1, January 1991, pp. 179-189.**

"Various methods have shown indirectly that insufficient time for diffusion of the hydration products and the large pores that form as a result are responsible for the reduction in strength of concretes cured at elevated temperatures."

"This paper describes an examination of the developing microstructure of cement pastes hydrated at 5-50 °C (41-122 °F)." Results show "...that low curing temperatures result in a uniform distribution of hydration products, while elevated temperatures result in a coarsened pore structure. [...] Compressive strengths of companion mortar specimens are consistent with the observed pore structure of the pastes."

Summary and Conclusions:

- "The morphology of the CH crystals is generally lamellar and elongated when the hydration temperature is low, but more compact when the temperature is higher."
- "The pores are finely distributed when the hydration temperature is low except for some large, isolated pores...."
- The formation of "...hydration shells are more apparent in the specimens hydrated at 50 °C (122 °F) and not at all apparent in the 5 °C (41 °F) specimens."

NOTE: Items numbered 4.5 through 4.9 below are preprints of papers presented at the **CANMET/ACI INTERNATIONAL WORKSHOP ON THE USE OF SILICA FUME IN CONCRETE,** WASHINGTON, D.C., APRIL 7 - 9, 1991

4.5 **Khayat, K. H. and Aitcin, P. C., SILICA FUME IN CONCRETE - AN OVERVIEW, pp. 1-46.**

Curing:

The authors state that "...the majority of strength gain due to SF [silica fume] addition takes place in the first 28 d. However, in order to take advantage of the SF addition, the concrete should be properly cured at early ages. This is important since SF concrete is sensitive to self-desiccation. Petersson et al. (1983), Loland and Hustad (1981), and Asselanis et al. (1989) suggest that SF concrete should be moist-cured for at least 5 to 7 d before any drying.

Maage and Hammer (1985) showed that the tensile strength of SF concrete allowed to dry after demolding had a 15 to 35% reduction in tensile strength after 3 months of curing compared to that of moist-cured concrete. This was significantly greater than strength reduction of dry concrete made without SF."

4.6 Gjorv, O. E., NORWEGIAN EXPERIENCE WITH CONDENSED SILICA FUME IN CONCRETE, pp. 47-64.

"Extensive experience has shown that CSF [condensed silica fume] in concrete reduces the permeability more than it improves the compressive strength. Thus, by proper use of CSF it is possible to achieve very durable concrete even for very aggressive environments."

4.7 Read, P., Carette, G. G., and Malhotra, V. M., STRENGTH DEVELOPMENT CHARACTERISTICS OF HIGH-STRENGTH CONCRETE INCORPORATING SUPPLEMENTARY CEMENTING MATERIALS, pp. 83-110.

"This paper presents data at ages up to two and a half years on the strength development characteristics of high-strength concrete {>80 MPa (11,600 psi)} incorporating blast-furnace slag and/or silica fume or high volumes of ASTM Class F fly ash.

Six concrete mixtures of various compositions were investigated in this study."

"In general, the early-age strength development of test cylinders did not appear to be greatly influenced by the curing condition. Their long-term strength development, however, is clearly shown to be affected by the type of curing; for all six concretes the compressive strengths of the moist-cured cylinders were higher than that for the air-dried specimens at 6 months and all later ages. The silica fume and the slag concretes generally seemed to be the least affected by curing regime.

The mixture with a high content of fly ash was the most affected, with a strength difference between the moist-cured and air-cured specimens of 29.6 MPa (4,300 psi) at 30 months. It should be noted, however, that the latter concrete, when moist-cured, exhibited, along with the control and the 12 percent silica fume concretes, the highest strength at thirty months with values in excess of 100 MPa (14,500 psi)."

"Immediately after casting each cylinder specimen mould [sic] was covered with a plastic bag and half were placed in a moist-curing room while the other half remained in the laboratory. Twenty-four hours after casting, all cylinders were demoulded [sic]. The moist-room specimens were then returned to the moist-curing room {23 °C (73.4 °F), RH>95}, and the other half was stored under wet burlap in the laboratory for seven days, then air-cured alongside the appropriate outside concrete element thereafter."

"For each type of concrete mixture, three test elements were cast...." They were a thick-wall element, a thin-wall element, and a high block to represent a thick column.

For each of the test elements, the formwork was removed between 18 and 24 hours after casting. "The elements were then cured under wet burlap for...six days. Thereafter, a waterproofed plywood roof was erected over the test site to protect the cast elements and air-cured cylinders from the direct effects of weather, particularly access of moisture and sun. The sides of the test site were left unprotected, thus simulating the exposure condition of concrete columns and walls during a typical multi-story construction. The air-curing environment was therefore variable, following seasonal temperature and humidity variations."

"In general, regardless of the curing conditions, the mixtures containing silica fume had a faster rate of strength development up to the age of 28 days, after which their strength gains were generally lower than those for the other concrete mixtures up to 365 days. The highest rate of strength development between 28 and 365 days was observed with the high-volume fly ash concrete, which is primarily due to the pozzolanic action of fly ash. For all mixtures, strength changes after one year were relatively small."

"The within-test variations for the cylinder strength results were, with a few minor exceptions, generally small and they were essentially independent of the type of mixture, the age of test and the condition of curing...."

4.8 **Ozyildirim, C., CONCRETE BRIDGE-DECK OVERLAYS CONTAINING SILICA FUME, pp. 305-312.**

"Plastic shrinkage [of silica fume concrete] is of concern, and the necessary measures to prevent this must be taken. The rate of evaporation from the surface during placement and texturing must be minimized. This is usually achieved by the use of fog spraying or misting. The curing material must be applied immediately. Insulating blankets are also found to be very effective in retaining moisture in the concrete as well as in retaining the heat of hydration, which are highly desirable for pozzolanic materials."

4.9 **Ho, D. W. S. and Lewis, R. K., PRELIMINARY STUDY ON THE STABILITY OF A SILICA FUME CONCRETE, pp. 143-154.**

It is well known that curing is one of the most neglected processes in concrete construction.

It has been found that on-site curing is often of a short duration and forms are often removed one day after the placement of the concrete with no additional moist curing. "Although on-site curing is limited, it is often argued that concrete will be cured once it is exposed to the weather because of the subsequent wetting by rain."

"At strengths below 40 MPa (5,800 psi), results indicate that silica fume mixes are more sensitive to the lack of initial curing."

"Climate and service conditions vary, and they...have a significant influence on the curing quality of concrete."

Summary:
"After one year of outdoor exposure, the quality of concrete, as indicated by water sorptivity, was found to have changed possibly due to intermittent wetting and drying. Some concretes improved while others showed the opposite trend. This phenomenon seems to be associated with the portland cement used and its interaction with the particular silica fume. The mechanism of this observed phenomenon can be complex and more work will be needed before explanations can be offered and prediction made."

4.10 **Larrard, F. de and Bostvironnois, J. L., ON THE LONG-TERM STRENGTH LOSSES OF SILICA-FUME HIGH STRENGTH CONCRETES, Magazine of Concrete Research, Vol. 43, No. 155, June 1991, pp. 109-145.**

Distinguishes between high strength concrete (HSC) {50 to 80 MPa (7,250 to 11,600 psi)} and very high strength concrete (VHSC) {greater than 80 MPa (11,600 psi)}. Results show continuous growth of the compressive strength of silica fume concretes cured in water; some authors have found reductions in strength in the first years when they are cured in air. Losses of compressive strength of test cylinders are attributed to drying. Drying from the surface leads to moisture gradients, which induce self stresses in the specimens. It is argued that this loss of strength does not exceed twice the tensile strength of the concrete.

4.11 **Carino, Nicholas J. and Clifton, James R., HIGH-PERFORMANCE CONCRETE: RESEARCH NEEDS TO ENHANCE ITS USE, Concrete International, Vol. 13, No. 9, September 1991, pp. 70-76.**

This is a summary of the workshop reported in Reference 4.3.

Definition of high-performance concrete (HPC): "Concrete having desired properties and uniformity that cannot be obtained routinely using only traditional constituents and normal mixing, placing, and curing practices. As examples these properties may include:

- Ease of placement and compaction without segregation.
- Enhanced long-term mechanical properties.
- High early-age strength.
- High toughness.
- Volume stability.
- Long life in severe environments."

"While important research programs are in place in the U. S., there is no overall program to coordinate the nation's efforts to understand HPC and to develop design criteria for its safe use. To fill the gap and to ensure that the U. S. remains a leader in concrete technology, NIST [the National Institute of Standards and Technology] proposed the initiation of a national program on HPC."

One of the goals of the NIST/American Concrete Institute workshop held in May, 1990 was to: "Develop a listing of critical research needs to overcome the technical barriers and provide a sound basis for new standards."

"The in place quality of a given HPC mixture is largely controlled by the mixing, placing, and curing conditions. Improved understanding of the relationships between these factors and the quality of HPC is needed to ensure that the desired properties will be attained."

"HPC will typically have low permeability that may restrict the movement of moisture into and out of concrete elements. There is a question whether this low permeability is an asset or a drawback during the curing period. Also, HPC usually does not bleed, and surface cracking due to drying can develop if the evaporation of moisture is not curtailed. Information is needed on the effectiveness of current practices for moist curing and evaporation control. The effects of the curing methods on the near-surface quality of the hardened concrete should be investigated."

One of the primary research needs is to determine the effects of curing conditions on HPC.

With respect to measuring strength, one factor that needs to be considered is the effect of initial curing conditions.

In some HSC research studies, "...core strengths have been found to be substantially lower than the standard-cured cylinder strengths. Some have suggested that the differences are due to unfavorable curing conditions in the structure."

In HPC "...temperature rise in structures due to heat of hydration is greater than in conventional mixes. [...] There is a need for fundamental understanding of the relationship between early-age temperature history and long-term properties."

"In addition to high temperatures, elements cast with HPC may also experience higher thermal gradients."

A durability design standard should be developed for HPC.

"The first objectives of new research programs should be to establish which of the current criteria are not applicable to HSC."

"Current design criteria are based largely on tests of components with concrete strength less than about 40 MPa (6,000 psi). Comprehensive tests to verify the applicability of existing criteria to HSC members are needed [with respect to strength and performance]."

"For proper modeling of thermal history, tests of HPC components should be performed on full-scale specimens. If scale models are used, special curing procedures should be used to simulate the temperature rise in full-scale members. Attention should also be paid to structural performance as a function of concrete maturity."

"To instill confidence in the use of HPC, new standards and acceptance criteria based on understanding the factors controlling the performance of HPC are needed."

"In place testing as a means for acceptance of new construction needs to be promoted."

"Implementation of a national program on HPC should be given top priority."

HPC is likely to play an important role in the rebuilding of the nation's infrastructure.

4.12 **Zia, Paul, Leming, Michael L., and Ahmad, Shuaib H., HIGH PERFORMANCE CONCRETE—A STATE-OF-THE-ART REPORT, SHRP-C/FR-91-103, NCSU, 1991.**

The definition of high-performance concrete is related strength development characteristics and resistance to freezing and thawing. HPC can be defined as concrete with:

1. a maximum W/C ratio of 0.35
2. a minimum Durability Factor of 80%, as determined by ASTM C 666, Method A
3. one of the following minimum strength requirements:
    a. 21 MPa (3,000 psi) within 4 hours after placement (VES), or
    b. 34 MPa (5,000 psi) within 24 hours after placement (HES), or
    c. 69 MPa (10,000 psi) within 28 days after placement (VHS)

These types are explained further:

"**Very Early Strength** (VES) concrete will have a compressive strength of at least 21 MPa (3,000 psi) within 4 hours after placement. No curing of the concrete is expected after the first 4 hours although continued curing would be beneficial. When longer curing periods are available, it is unlikely that this type of material would be used for new pavement due to cost."

High Early Strength (HES) concrete will have reached a compressive strength of at least 34 MPa (5000 psi) within 24 hours. "This type of concrete, when used in a pavement, would be placed by machine and receive little or no curing after 24 hours. It would be expected to provide very long-term serviceability."

"**Very High Strength** (VHS) concrete will have a compressive strength of 69 MPa (10,000 psi) at 28 days. This concrete will have primary applications in bridge construction where time for long-term curing is available and structural efficiency is at a premium."

"Concrete with a W/C ratio of 0.35 will produce a discontinuous capillary system in about a day of moist curing, which will provide improved durability to chemical attack, freeze-thaw cycling and wetting and drying. Therefore, all high performance concrete will have a maximum W/C ratio of 0.35."

"The quality of high performance concrete is, like all concretes, ultimately limited by the quality of the raw materials used, the level of quality management exercised in production, and the care maintained in handling and curing."

"It has been reported [by Asselanis, Aitcin, and Mehta in 1989] that moist curing of low W/C ratio (0.3) concrete containing silica fume past seven days will not substantially increase the compressive strength since the concrete has become impervious.... [...] Concrete containing silica fume has been reported to be more susceptible to strength loss due to early drying than conventional concrete at the same W/C ratio. Concrete with silica fume has also been found to be more sensitive to curing conditions, especially premature drying....

The use of nonbleeding concrete in a slipform paving operation will require the immediate application of curing compound or other methods of reducing moisture loss. This will improve strength in place and reduce the potential for plastic shrinkage cracking.

Temperature of the concrete after casting should be controlled by the use of insulating blankets. Even in warm weather, the use of a blanket may reduce cracking by reducing the temperature differential between the surface and center or bottom of the pavement and therefore reducing stresses at early ages while the concrete has limited tensile strength."

"The use of steel or sturdy plastic molds is recommended, as the member is cured until design age for HES and VES mixes or cured according to ASTM standards for VHS mixes. ASTM C 31, Standard Method of Making and Curing Concrete Test Specimens in the Field, calls for keeping test cylinders at 16 to 27 °C (60 to 80 °F) for the first 24 hours, protected from evaporation. For low W/C ratios, protection from evaporation will be critical. Special precautions should be taken to insure no initial moisture loss."

"The efficiency of silica fume in producing concrete of higher strength depends on water/cement + silica fume ratio, dosage of silica fume, age and curing conditions."

"Strength development with time is a function of the constituent materials and curing techniques. An adequate amount of moisture is necessary to ensure that hydration is sufficient to reduce the porosity to a level necessary to attain the desired strength level.

Although cement paste in practice will never completely hydrate, the aim of curing is to ensure sufficient hydration. In pastes with lower W/C ratios, self desiccation can occur during hydration and thus prevent further hydration unless water is supplied externally."

High strength concrete (HSC) gains strength at a higher rate at early ages. "At later ages the difference is not significant." Test "...data indicate that for moist-cured specimens, strengths at 56 days are about 10% greater than 28 day strengths. Strengths at 90 days are about 15% greater than 28 day strengths."

"Curing at elevated temperatures has a greater accelerating effect on condensed silica fume (CSF) concrete than on control concrete. [...] Curing at temperatures below 20 °C (68 °F) retards strength development more for CSF concrete than for control concrete." It is evident that CSF concrete is more sensitive to curing temperature than ordinary portland cement concrete.

"Curing techniques have significant effects on the strength. The key concerns in curing, especially for HSC, are maintaining adequate moisture and temperatures to permit continued cement hydration. Water curing of higher strength concrete is highly recommended...due to its low W/C ratio. At W/C ratio below 0.40, the ultimate degree of hydration is significantly reduced if free water is not provided. The effects of two different curing conditions on concrete strength were investigated [by Carrasquillo, Slate, and Nilson as reported in 1981].... The two conditions were moist curing for 7 days followed by drying at 50% relative humidity until testing at 28 days, and moist curing for 28 days followed by drying at 50% relative humidity until testing at 95 days. Higher strength concrete showed a larger reduction in compressive strength when allowed to dry before completion of curing." It was reported in 1988 by Carrasquillo and Carrasquillo that the strength is higher with moist curing as compared to field curing.

"It is generally accepted that regardless of the mix proportions or curing age, concrete specimens tested in wet conditions show about 15% higher elastic modulus than the corresponding specimens tested in dry conditions.... This is attributed to the effect of drying on the transition zone. Because of drying, there is microcracking in the transition zone due to shrinkage, which reduces the modulus of elasticity."

"In a recent study [Collins, 1989], it was shown that for five mixes with 28-day design strengths ranging from 60 to 64 MPa (8,700 to 9,300 psi), the shrinkage deformation was inversely proportional to the moist-curing time (the longer the curing time, the lower the shrinkage). It was...concluded that shrinkage was somewhat less for concrete mixtures with lower cement paste and larger {38 mm (1.5 in.)} aggregate size. In addition, the use of a high range water reducing admixture did not have a significant effect on the shrinkage deformation."

"It is generally recognized that concrete cast and cured at low temperatures develops strength at a significantly slower rate than similar concrete placed at room temperature."

HSC "...shows less susceptibility to decreasing temperatures as compared to normal strength concrete."

"Porosity and permeability are...greatly affected by curing. It was shown by Powers et al. [in studies from the 1950's] that for a given W/C ratio, the permeability of cement paste can be reduced significantly with increased time of moist curing...."

As reported in 1987, "...Senbetta and Malchow...studied the effects of different curing methods on the various properties of concrete with a given mix design. They compared air cure with wax sealing, plastic cover, moist cure, and two different kinds of curing compound, all applied for 14 days. The results demonstrated that moist cure, wax sealing, and plastic cover were far superior (by several orders of magnitude) than the other three curing procedures with respect to abrasion resistance, shrinkage, resistance to corrosion of steel in concrete, chloride ion concentration in concrete, and absorptivity.

In a series of tests by Thomas et al. [1989] ..., the effect of curing on the strength and permeability of fly ash concrete was studied. Concrete specimens designed to have equal workability and 28 day compressive strength but with a range of fly ash contents were subjected to a range of moisture-curing periods prior to air storage. Compressive strength was then determined at various ages and permeability to oxygen and water was determined at 28 days. The results clearly indicate the importance of curing. Reductions in curing period produced lower-strength and more-permeable concrete. However, even though the strength of fly ash concrete was more sensitive to poor curing than that of the ordinary portland cement concrete, fly ash concretes moist-cured for only one day were in general no more permeable to water and much less permeable to oxygen than similarly cured concrete without fly ash."

"It is clear that the strength and the permeability of a concrete are interrelated through its porosity. Alternatively, W/C ratio and curing may be viewed as the common links between strength and permeability. Therefore, a high performance concrete is generally also a high quality, durable concrete of low permeability."

4.13 **Malhotra, V. M. and Carino, N. J., CRC HANDBOOK ON NONDESTRUCTIVE TESTING OF CONCRETE, CRC Press, Chapter 5, The Maturity Method, 1991, pp. 101-146.**

The maturity method is "...a technique for estimating the strength gain of concrete based upon the measured temperature history during curing. The combined effects of time and temperature on strength gain are quantified by means of a maturity function." The maturity method can only be used to estimate relative strength during the curing period.

"As is well known, the strength of a given concrete mixture, which has been properly placed, consolidated and cured, is a function of its age and temperature history. At early ages, temperature has a dramatic effect on strength development. This temperature dependence presents problems in trying to estimate the in-place strength based on strength development data obtained under standard laboratory conditions."

The author states that "...the maturity method is viewed as a useful and simple means for accounting approximately for the complex effects of time and temperature on strength development."

"Maturity functions are used to convert the actual temperature history of the concrete to a factor which is indicative of how much strength has developed."

Equivalent age "...represents the duration of the curing period at the reference temperature which would result in the same value of maturity as the curing period at other temperatures." A ratio is used, called the "age conversion factor," to convert a curing interval to the equivalent curing interval at the standard reference temperature.

It has been shown "...that a maturity function based on the product of time and temperature above a datum value cannot account for the 'quality of cure' as affected by initial curing temperature."

"As a result of its investigations of construction failures involving concrete, the U.S. National Bureau of Standards (NBS) undertook research on the application of the maturity method as a tool for estimating in-place strength of concrete at early ages." Lew and Reichard reported in 1978 that "...development of indirect tensile strength, modulus of elasticity and pullout bond strength of steel bars under different curing temperatures could be related to maturity."

Tests conducted by NBS indicated that specimens with higher early-age temperatures resulted in lower long-term strength. It was also clear there was not a unique strength-maturity relationship for a single concrete mixture. "Subsequent tests at the NBS confirmed the importance of early-age temperature on the resulting strength-maturity relationship, and it appeared that 'early age' could be as early as the first 6 hr."

This chapter reviewed some of the proposed functions to represent the relationship between maturity and strength development.

"Regardless of which relationship is chosen, the key point is that the coefficients which define the exact shape of the curves depend on the particular concrete mixture."

The development of a mathematical expression to describe the compressive strength development of concrete is presented using ideas from Bernhardt in 1956. "The rate of strength gain (*dS/dt*) at any age (*t*) is assumed to be a function of the current strength (*S*) and the temperature (*T*), i.e.,

$$\frac{dS}{dt} = f(S) \cdot k(T)$$

where

$f(S)$ = a function of strength and
$k(T)$ = a function of temperature [called the rate constant]."

The concept is introduced that strength gain does not begin until some time after mixing. This accounts for the induction period between initial mixing and the start of strength gain.

"Knudsen's assumption [from his work in the early 1980's] that cement particles react independently is significant. As is well known, hydration products form in the water-filled spaces between cement particles. As the water-cement ratio is lowered, the distance between cement particles is reduced. Therefore, particle interference increases and one would expect the hydration rate to decrease. [...] Knudsen concluded that the assumption of independent particle reaction was not seriously violated at a water-cement ratio as low as 0.4. Thus it is expected that the rate constant should be independent of the water-cement ratio during the early stages of hydration."

"If one wishes to use a linear maturity function because of its simplicity, accuracy can be improved greatly by using two values of the datum temperature. One value would be applicable when the curing temperature is below the reference temperature and the other would be used above the reference temperature."

"It has been firmly established that the degree of hydration of cement correlates with the mechanical strength of concrete. Thus it is possible to determine the activation energy from hydration studies of cement pastes. This approach is supported by the work of... [several researchers] who have shown that the activation energies based upon heats of hydration are the same as those based upon the mechanical strength of mortars."

"Presently there is not much published data on the activation energy for strength development of concrete."

More research is needed to determine how water-cement ratio relates to the activation energy. The activation energy indicates the sensitivity of the rate constant to temperature.

"Due to the scarcity of data, there does not yet exist a thorough understanding of the factors which affect the activation energy. As more data are accumulated, it may be possible to predict the activation energy of a particular cement based upon its chemical composition. When admixtures or cementitious additions are used, their effects on the activation energy must also be determined. This can probably only be done by testing the combinations of cement and admixtures that will be used."

"It is clear that the curing temperatures affect not only the initial rate of strength development but also the limiting strength."

It has been shown that "...while the early-age temperature affects the long-term strength, there is no significant effect of curing temperature on the relationship between equivalent age and relative strength."

The **modified maturity rule** can be stated as follows: "Samples of a given concrete mixture which have the same equivalent age and which have had a sufficient supply of moisture for hydration will have equal fractions of their limiting strength irrespective of their actual temperature histories."

"The significance of this modified maturity rule is that if one measures only the temperature of concrete while it is curing, only the relative strength gain can be estimated."

Research has shown that "...under isothermal conditions, the strength gain of concrete can be described by a hyperbolic curve defined by three parameters: (1) the age when strength development is assumed to begin...; (2) a rate constant...which is related to the initial slope of the curve; and (3) the limiting strength...." These parameters are temperature dependent.

One of the key elements "...in arriving at a valid maturity function is describing the relationship between the rate constant and the curing temperature."

"Tests have shown that over a wide temperature range, the rate constant is a nonlinear function of temperature. [...] It is not clear whether water-cement ratio has a consistent effect on activation energy. For concretes made with ordinary portland cement and without admixtures, it appears that the activation energy is between 40 and 45 kJ/mol."

It is known that "...the limiting strength of a concrete mixture is affected by the early-age temperature history. Thus there is not a unique strength-equivalent age relationship for a given concrete. However, there is a unique relative strength vs. equivalent age relationship." The modified maturity rule proposes that "...relative strength can be reliably estimated from the measured temperature history. In order to estimate absolute strength level, additional information about the concrete is required."

The maturity method "...may be used to estimate in-place strength to assure that critical construction operations, such as form removal or application of post-tensioning, can be performed safely. It may be used to decide when a sufficient amount of curing has occurred and the concrete can be exposed to ambient conditions without endangering its long-term performance. In addition, it may serve as a tool in planning construction activities."

"Proper curing procedures must be used to apply the maturity method for estimating strength development. It is essential that there is an adequate supply of moisture for hydration. If concrete dries out, strength gain ceases but the computed maturity value continues to increase with time. In such a case, strength estimates based upon the maturity method are meaningless."

"The temperature history of the structure is the basic information needed to evaluate the in-place maturity (expressed as the temperature-time factor or equivalent age). Therefore, a device is needed to record temperature as a function of time."

"Maturity meters" are commercially produced instruments capable of monitoring the temperature history and automatically performing the maturity calculations.

Currently, "...a variety of commercial devices are available which can automatically compute the in-place maturity."

The author reminds users of the maturity method that "...it is not prudent to rely solely on measurements of in-place maturity to verify the attainment of a required level of strength before performing a critical construction operation." Maturity testing should be supplemented with other tests.

Application of the maturity method requires three elements: "(1) the maturity function for the concrete materials; (2) a strength-maturity relationship for the concrete mixture to be used in construction; and (3) measurement of the in-place thermal history." The proper maturity function can be obtained using a testing procedure with mortar cubes.

"The strength-maturity relationship is obtained from strength development data of concrete specimens."

"The equivalent age approach is the most flexible technique to represent maturity. In this case, the age factor is used to convert a curing time interval at any temperature to an equivalent time interval at a reference temperature. The age factor is simply the ratio of the value of the rate constant at any temperature to its value at the reference temperature."

"Because of the dependence of the limiting strength on the early-age curing temperature, a unique strength-maturity relationship does not exist for a given concrete mixture. However, it appears that there is a unique relative strength vs. maturity relationship. Thus, the only reliable information that can be obtained from measuring in-place maturity is relative strength gain."

The author summarizes, "...the maturity method provides a simple procedure to account for the effects of temperature and time on strength development. In combination with other in-place tests, the maturity method is expected to play an important role in advanced concrete technology."

4.14 **Carino, Nicholas J. and Tank, Rajesh C., MATURITY FUNCTIONS FOR CONCRETE MADE WITH VARIOUS CEMENTS AND ADMIXTURES, ACI Materials Journal, Vol. 89, No. 2, March-April 1992, pp. 188-196.**

The authors state that "...a 'maturity function' is used to convert the measured temperature history of the concrete to a numerical index indicative of the extent of strength development. Concrete strength is estimated during the curing period based upon the measured maturity index and the 'strength-maturity relationship' for that particular concrete mixture."

The goal of the study reported in this article "...was to develop a reliable model to quantify the effects of curing temperature on the strength development of concrete."

"Equivalent age is a maturity index, and it represents the age at the reference curing temperature that would result in the same fraction of the limiting strength as would result from curing at other temperatures."

The article says, "...to estimate the relative strength gain of a given concrete mixture, the actual temperature history of the concrete is converted to an equivalent age at the reference temperature." Then the "rate constant model" equation is used to estimate the relative strength.

"The quantitative effect of curing temperature on the limiting strength is an important practical problem deserving further study." Tests showed that "...the age at the start of strength development...decreased with increasing curing temperature."

"The effect of w/c [ratio] on the B-value [temperature sensitivity factor] deserves additional study because it determines whether the same maturity function can be used for different strength grades (different w/c) of concrete made with the same cementitious materials."

This article proposes a procedure that "...has been developed for implementing the maturity method that will result in reliable estimates of in-place relative strength development. It is proposed that mortar tests will provide the necessary information to define the relative strength gain of concrete."

4.15 **Carino, Nicholas J., Knab, Lawrence I. and Clifton, James R., APPLICABILITY OF THE MATURITY METHOD TO HIGH-PERFORMANCE CONCRETE, NISTIR 4819, National Institute of Standards and Technology, May 1992.**

This was a study to determine if the maturity method is applicable to represent the strength development of high-performance concrete cured at different temperatures. It was concluded that this method is applicable for the low water-cement ratio mixtures used in this study (0.29 and 0.36). Another interesting conclusion from this report is that the estimated long-term strength did not appear to be affected by the curing temperature. This is inconsistent with the known behavior of conventional concrete mixtures. This indicates that the long-term strength of high-performance concrete may not be adversely affected by high curing temperatures as is the case with normal strength concrete mixtures.

The authors point out that additional research is needed before making a general conclusion regarding the applicability of the maturity method to all high-performance concrete mixtures. Additional work is also needed to verify that the use of mortar cubes to develop the maturity function and relative strength versus maturity index relationship is appropriate for high-performance concrete. More research is needed to corroborate the important finding related to the insensitivity of the limiting strength to the curing temperature.

This report contains an excellent summary/review of the background and history of the development of the maturity method. Three different strength-age models were investigated to determine which one would provide the best fit for the data. The investigation "...showed that none of the models was deemed to be clearly superior in describing the strength development of various mortar batches." This study did show that the linear-hyperbolic model is preferable when isothermal curing is used to obtain strength gain to determine the rate constant value at different temperatures. "When it is necessary to model long-term development with isothermal curing, the parabolic-hyperbolic model is the better choice...." The exponential model was found to be a poor choice under any condition for implementing the maturity method.

4.16 **Parrott, L. J., WATER ABSORPTION IN COVER CONCRETE, Materials and Structures, Vol. 25, No. 149, June 1992, pp. 284-292.**

"Measurements of initial water absorption are reported for concretes exposed indoors or outside for 1.5 years. Water absorption after a given wetting time was increased with an increase of water/cement ratio, a reduction of moist curing and partial replacement of the portland clinker component of the cement. Absorption after outdoor exposure was less than that after laboratory exposure, especially if rain could fall on the concrete surface. Absorption results correlated approximately with weight losses during initial exposure and with compressive strengths at the start of exposure. There was a near-linear relationship between carbonation depths and absorption measured in cover after 1.5 years of exposure."

"Carbonation will normally cause a counterbalancing reduction of capillary porosity in the outer layers of cover concrete."

"Water absorption is particularly relevant to concrete durability: freeze-thaw damage, sulphate attack, disruptive alkali-aggregate expansion, chloride ingress and reinforcement corrosion can be stimulated by water absorption, while carbonation will be inhibited."

The research reported by this author considered the effects of five exposure conditions, five w/c ratios, three periods of moist curing, and four cements upon water absorption.

"The test specimens were cured at 100% relative humidity and 20 °C (68 °F) in their moulds [sic] up to an age of 24 h. Subsequent moist curing involved storage in sealed conditions at 20 °C (68 °F) (without loss or gain of moisture). The laboratory conditions during exposure were 58 ± 3% relative humidity and 20 ± 1 °C (68 ± 2 °F)."

"Curing beyond 3 days reduced the absorption levels for concretes made with pulverized fuel ash or ground granulated blast furnace slag but for ordinary portland cement concrete long-term curing had only a small effect. When portland cement was partially replaced with pulverized fuel ash or ground granulated blast furnace slag it was necessary to increase the curing time from 3 to 28 days in order to achieve similar absorption results; this is consistent with European code requirements for longer curing periods when these cements are used at constant water/cement ratio. The sensitivity of absorption to the effects of curing has encouraged its use for evaluating the effectiveness of membranes and sheet materials as concrete curing aids...."

Although additional studies are required, the author states that "...it seems possible that high water absorption results could be indicative of high rates of long-term carbonation and vice versa."

4.17 **Bentz, D. P. and Garboczi, E. J., MODELLING THE LEACHING OF CALCIUM HYDROXIDE FROM CEMENT PASTE: EFFECTS ON PORE SPACE PERCOLATION AND DIFFUSIVITY, Materials and Structures, Vol. 25, No. 123, November 1992, pp. 523-533.**

"Using computer simulation, this paper examines the effects of calcium hydroxide dissolution on two material properties: the percolation properties or connectivity of the capillary pore space, and the relative ionic diffusivity. [...] Percolation theory is used to develop the concept of a critical volume fraction of calcium hydroxide plus capillary pore space." Results showed "...that this critical combined volume fraction determines the magnitude of the effect of leaching on relative ionic diffusivity."

Conclusions:
The study showed "...that leaching can increase the relative diffusivity by an order of magnitude or more, and change the connectivity of the capillary pore space of neat portland cement paste. Silica fume...[is] effective in minimizing these effects by reducing the calcium hydroxide content of cement paste."

The concept of a critical calcium hydroxide volume fraction + capillary porosity of about 18% has been developed and discussed in this article. "If this threshold is not exceeded, then any increase in the relative diffusivity of a paste due to leaching will be minimal. At a constant degree of hydration, improvements in reducing the detrimental effects of leaching on transport properties can be achieved by either reducing the w/s [water to solids] ratio or increasing the silica fume content up to but not exceeding the values... [determined to be the minima as reported in this study]."

This study shows the importance of considering not only the structural design requirements of a cement-based material, but also the durability design requirements for material exposed to the environment.

4.18 Ho, D. W. S., THE EFFECTIVENESS OF CURING TECHNIQUES ON THE QUALITY OF CONCRETE, Technical Report TR92/3, Australia, 1992.

This is a report on research done in Australia.

"This report discusses and provides quantitative data on the performance of various water-retaining curing techniques, including the use of moist sand, formwork, polyethylene sheet cover and curing compounds. Steam curing was also investigated. Both laboratory specimens and full-sized columns were considered. The surface quality of concrete was measured by water sorptivity, carbonation and abrasion resistance.

In general, with water-retaining curing techniques, it was found that there was significant improvement in the surface quality of concrete when cured to three days, and some additional improvement when curing was extended to seven days, but hardly any benefit arose when curing was extended beyond this time. The quality of concrete achieved with seven days of water-retaining curing techniques is equivalent to about three days of standard moist curing."

Three grades of concrete were used—25, 32, and 40. Their 28-day, water-cured strengths were 28 MPa (4,000 psi), 35 MPa (5,000 psi), and 45 MPa (6,500 psi), respectively.

The following conclusions can be drawn from the results of this study:

These results are applicable "...to concrete elements having a high surface area to volume ratio, i.e., thin sections such as walls and facades of buildings.

(a) All practical curing procedures improve the quality of concrete over that achieved with 1 day in the formwork. The surface quality achieved is generally equivalent to about 3 days of standard curing. Thus, so-called 'water-retaining' curing is less effective than 'water-added' curing.

(b) There is significant improvement in the surface quality when cured to 3 days and some additional improvement when the practical curing is extended to 7 days, but little or no benefit arises from curing beyond this time.

(c) Plastic envelope curing is only efficient if the integrity of the process is not destroyed by holes, tears or other gaps. Tight supervision is required to ensure a satisfactory performance of plastic envelopes.

(d) The wax membrane generally gives a higher surface quality than chlorinated rubber when used on vertical surfaces. The improved performance of the chlorinated rubber membrane for horizontal surfaces, relative to the wax membrane, may be due to the dilution by surface moisture of the water-based wax material.

(e) In general, the form of practical curing was less critical for 40 grade concrete than for lower grade concretes.

(f) Horizontal surfaces respond to curing in a similar manner to vertical surfaces.

(g) Steam curing gives an ex-steam quality similar to other curing procedures (i.e., 3 days of standard curing). Additional water curing after steam curing provides only marginal benefit.

(h) Abrasion resistance is generally improved by practical curing. The greatest improvements occur with the 40 grade concrete."

The following conclusions are "...appropriate to concrete elements having a low surface area to volume ratio, i.e. thick elements such as square or round columns of buildings.

(a) Self-curing is evident for columns even after 7 days of air drying, leading to an improved quality equivalent to 2-3 days of standard curing. However, this may not be so where self-desiccation exists, as in the case of concrete with a very low w/c ratio.

(b) Seven days of practical curing approaches the equivalent quality of 7 days standard curing, but extended practical curing beyond 7 days gives little benefit."

It should be noted that standard curing refers to curing in a fog room at 23 °C (73 °F), whereas practical curing refers to any other form of curing addressed in this report, such as plastic envelope, curing membranes, moist sand, and formwork, all of which would be appropriate to on-site field conditions.

4.19 Hooton, R. D., INFLUENCE OF SILICA FUME REPLACEMENT OF CEMENT ON PHYSICAL PROPERTIES AND RESISTANCE TO SULFATE ATTACK, FREEZING AND THAWING, AND ALKALI-SILICA REACTIVITY, ACI Materials Journal, Vol. 90, No. 2, March-April 1993, pp. 143-151.

"The use of silica fume in concrete has become widespread in North America in the areas of both high-strength concrete and where durability is of prime concern...." The author states that "...little data has been published with respect to the effects of silica fume on permeability, as well as resistance to sulfate attack and alkali-aggregate reactivity." Results are presented in this paper for silica fume replacements of 5 to 20 percent by mass of the cement.

"After 7 days of moist-curing, the compressive strengths of all of the SF mixes were 34 to 57 percent higher than the control, with higher increases as SF contents were increased. [...] At ages greater than 56 days, the SF concretes practically stopped developing strength, likely due to self-desiccation effects."

Silica fume used as a cement replacement provides "...higher resistance to sulfate attack, alkali-reactive aggregates, and freezing and thawing."

"It appears that a 10 percent by mass replacement of portland cement by silica fume is adequate with respect to resistance to freezing and thawing, sulfate attack, or alkali-silica reactivity, and does not result in a large increase in drying shrinkage. The early age strengths with 10 percent SF are not as high as with 15 or 20 percent, but 10 percent did not result in any increase in microcracking in the hardened concrete."

4.20 **Garboczi, E. J., COMPUTATIONAL MATERIALS SCIENCE OF CEMENT-BASED MATERIALS, Materials and Structures, Vol. 26, No. 158, May 1993, pp. 191-195.**

"Concrete can be considered to be a mortar-rock composite, where the randomness in the structure is on the order of a few centimeters, the size of a typical coarse aggregate."

The author "...found the ideas of percolation theory to be very helpful in understanding the relationship between the random microstructure of cement-based materials and their transport properties. The main concept of percolation theory is connectivity."

"A percolation threshold that is important for transport processes is the point at which the capillary pore space loses continuity. At this point, 'fast' transport of water or ions through the relatively large capillary pore system would end, and transport would then be regulated by the much smaller C-S-H gel pores."

Results of model studies showed "...that water/cement ratios of 0.6 and above always have a continuous (or percolated) capillary pore system." Results also showed "...that as the water/cement ratio decreases below 0.6, less and less hydration is required to close off the capillary pore system."

Studies show "...that there is a common percolation threshold at a critical value of capillary porosity of about 0.18." The reason that pastes with water-cement ratios greater than 0.6 always have an open capillary pore space is "...there is not enough cement present originally to be able to bring the capillary porosity down to the critical value, even after full hydration."

There are three regions of behavior for the transport properties of cement paste. "The first region is early in hydration, where the capillary pore space is fully percolated. [...] As the capillary porosity decreases, the capillary pores also become smaller, and so the second region is an intermediate region, for porosities around the percolation threshold, where pure capillary pore paths have about the same influence on flow as hybrid paths that are made up of isolated capillary pockets linked by C-S-H gel pores. Below the critical capillary porosity, all flow must now go through C-S-H gel pores, but the flow is still dominated by the hybrid paths, not just pure C-S-H gel pore paths."

4.21 **Ho, D. W. S. and Cao, H. T., WATER SORPTIVITY OF STEAM-CURED CONCRETE, Concrete Institute of Australia Seminar on the Structural Use of Precast Concrete, March 7, 1994, pp. 1-10.**

This paper addresses some of the issues relating to steam cured precast products. The authors state that the findings are not necessarily conclusive and more work is needed in many areas.

Preliminary studies on thermal curing were carried out "...in an attempt to answer some of the often-asked questions on the durability of steam-cured products. This paper presents results of these preliminary studies and it is important to emphasize [sic] that some of the findings are by no means conclusive, they merely provide the directions for future research."

"Durability of concrete has been a major concern for the construction industry particularly in the early 1980's. Through the sponsorship of the Cement and Concrete Association of Australia, ...the concept of water sorptivity [was developed], a property quantifying the ease at which water penetrates into concrete. This property is regarded as one form of permeability and is particularly relevant to above-ground structures."

The Roads and Transport Authority has adopted water sorptivity of concrete as one of the durability provisions to be incorporated in the mix design process. "This will have major ramifications for curing practices and will go a long way towards ensuring long-term resistance to concrete deterioration even in aggressive environments.

Water sorptivity is a property describing the rate of water penetration due to capillary action, and provides a useful indication of the pore structure of the concrete surface layer."

"In the laboratory, concrete is normally cured under standard conditions.... However, on-site concrete is rarely cured under conditions similar...[to those in the laboratory]. With cast-in-situ concrete, the common methods of curing are spraying the surface with a curing compound, maintaining formwork in place, or covering the surface with polyethylene. These methods are sometimes referred to as water-retaining techniques. With horizontal surfaces, water-adding techniques like ponding, wet hessian and damp sand are sometimes used. In the precast industry, concrete elements are often steam cured as this enables increased production resulting from better use of moulds [sic]."

"One question often asked is whether or not there is a need for subsequent moist curing after thermal curing." From studies conducted, "...it was found that the quality of concrete, as indicated by water sorptivity, was unchanged with subsequent moist curing."

"A further controversial issue is on the concept of maturity before the steam cycle is commenced. Maturity is often defined as the area under the curve of temperature-time graph. An initial maturity of 40 °C · h (72 °F · h) before steam is applied was found to be appropriate for curing cycles designed for one mould [sic] use per day. This means a delay period of 2 hours if the temperature of the concrete remains constant at 20 °C (68 °F)." [Note the above assumes a datum temperature of 0 °C (32 °F) in the Nurse-Saul maturity function.]

"The cost-effectiveness of precasting is strongly influenced by mould [sic] utilisation [sic] and, therefore, a performance based specification is urgently needed."

4.22 **Bartlett, F. Michael and MacGregor, James G., EFFECT OF MOISTURE CONDITION ON CONCRETE CORE STRENGTHS, ACI Materials Journal, Vol. 91, No. 3, May-June 1994, pp. 227-236.**

The length of the moisture conditioning periods specified for cores in ASTM C 42-90 or ACI 318-89 are too short to allow a uniform change of moisture to occur throughout the entire volume of the specimen.

"The implicit assumption in ACI 318-89 and in the provisions recommended by the Concrete Society, that the moisture conditioning effect observed on small core specimens can be extrapolated to concrete in large structures, seems unrealistic."

"The most accurate estimate of in situ concrete strength is obtained from a specimen with no gradient of moisture content through its volume. Such a specimen may be obtained using an air-cooled drill, or by letting excess water evaporate from cores obtained using a water-cooled drill. The 7 days of air-drying treatment permitted by ASTM C 42-90 and ACI 318-89 seems excessively long for letting excess cooling water evaporate."

"The compressive strength is...considerably affected if a moisture gradient is created between the exterior and interior of the specimen. Soaking the specimen causes swelling at the surface. [...] Drying the specimen causes shrinkage at the surface and increases the compressive strength."

4.23 **Hindy, Elie El, Miao, Buquan, Chaallal, Omar, and Aitcin, Pierre-Claude, DRYING SHRINKAGE OF READY-MIXED HIGH-PERFORMANCE CONCRETE, ACI Materials Journal, Vol. 91, No. 3, May-June 1994, pp. 300-305.**

"This paper reports on drying shrinkage undergone by ready-mixed high-performance concrete (HPC). Shrinkage measurements were carried out on concrete specimens as well as on instrumented reference columns. Two different HPC were tested. The first one had a compressive strength of 98 MPa (14,200 psi) at 91 days, and the second had a compressive strength of 80 MPa (11,600 psi). The first contained silica fume but the second did not.

The effects of the following factors were investigated: curing time, curing conditions, silica fume content, and water-cementitious materials ratio. It was found that the longer the curing time the lower the drying shrinkage, and that the lower the water-cementitious materials ratio the lower the drying shrinkage."

The authors state that "...high-performance concrete (HPC) is a relatively new material and therefore data on its shrinkage behavior are very limited."

For the study reported in this article, four instrumented columns were cast using commercial ready-mixed concretes.

"All specimens, including those for the shrinkage investigation, were cast on site. They were then covered with wet burlap overnight and transferred the following day to the laboratory and demolded.

The specimens for the shrinkage investigation and their curing conditions were as follows...:

1. Eight 100 x 375-mm (4 x 14 ¾ in.) cylinders and four 100 x 100 x 375-mm (4 x 4 x 14 ¾ in.) prisms, which were sealed first with a plastic sheet and then with an aluminum foil. The specimens were stored in the laboratory at 20 °C (68 °F) and a relative humidity of 50 percent.
2. Four 100 x 100 x 375-mm (4 x 4 x 14 ¾ in.) prisms which were placed in lime-saturated water at ambient temperature of 20 °C (68 °F).
3. Two 100 x 375-mm (4 x 14 ¾ in.) cylinders and two 100 x 100 x 375-mm (4 x 4 x 14 ¾ in.) prisms were stored in air, along with sealed specimens in laboratory conditions."

Some of the conclusions reached were:

- "Drying shrinkage of 98 MPa (14,200 psi) concrete with a water-(cement+silica fume) ratio of 0.22 was smaller than that of 80 MPa (11,600 psi) concrete with a water-cement ratio of 0.28 for the different curing conditions studied."

- "The influence of curing duration is more pronounced for the 80 MPa (11,600 psi) concrete than for the 98 MPa (14,200 psi) one. For both concretes, the longer the time of curing, the lower the drying shrinkage."

- "The drying shrinkage-mass loss relation for HPC is almost linear as in the case of normal strength concrete."

"The column strain increases due to shrinkage recorded on site between 70 and 330 days were negligible for the 98 MPa (14,200 psi) concrete and 20 x 10^{-6} for the 80 MPa (11,600 psi) one. When measured on air-cured samples in the laboratory, these strains were, respectively 162 x 10^{-6} and 227 x 10^{-6} during the same period of time. Obviously, this difference is due to the large volume/surface ratio of the columns as compared to that of laboratory specimens."

4.24 **Aitcin, Pierre-Claude, Miao, Buquan, Cook, William D., and Mitchell, Denis, EFFECTS OF SIZE AND CURING ON CYLINDER COMPRESSIVE STRENGTH OF NORMAL AND HIGH STRENGTH CONCRETES, ACI Materials Journal, Vol. 91, No. 4, July-August 1994, pp. 349-354.**

It is known that "...high strength concrete is sensitive to the way in which the ends are prepared, with lower strengths being obtained for cylinders prepared with standard capping compounds."

"To predict the development of compressive strength with time, it is necessary to account for the type of concrete, cylinder size, and type of curing."

For higher strength concretes, "...the compressive strength continues to increase over a longer period of time than that observed for low-strength concrete."

"The influence of cylinder size and curing on the measured compressive strength of different strength concretes was investigated as part of an overall research program aimed at obtaining the structural properties of high-strength concretes. Three batches of ready-mix concrete with target compressive strengths of 35, 90, and 120 MPa (5,000, 13,000 and 17,500 psi) were used to cast a large number of control specimens. Compression tests were performed on 100, 150, and 200 mm (4, 6, and 8 in.) diameter cylinders. The different curing conditions studied included air-cured, sealed, and water-cured. The tests were performed over a 1-year period to enable a study of the compressive strength gain."

"In the presence of water-curing, the 120 MPa (17,500 psi) concrete had the largest increase in compressive strength. The 13 percent increase in strength at 1 year, over companion sealed cylinders, could be due to further hydration of the high-strength concrete, which had a very low water-cement ratio of 0.25.

The larger the cylinder size, the larger the coefficient of variation on the compressive strength.

Larger cylinder sizes gave rise to lower apparent compressive strengths."

4.25 **Cather, Bob, CURING: THE TRUE STORY?, Magazine of Concrete Research, Vol. 46, No. 168, September 1994, pp. 157-161.**

The author states that "...compressive strength development in structures is one of the properties least sensitive to curing."

Two formal definitions of curing:

- Materials science: "curing is the creation of an environment in which hydration reactions can proceed to help fulfill the aim of producing concrete of adequately low porosity."
- Engineering: "curing is adequate when the resulting concrete achieves the expected service performance."

These definitions "...should be seen as complementary rather than as alternatives."

This article states that recent research has shown "...that small drops in relative humidity (RH) within the pores of the cement significantly reduce the rate of hydration."

Curing-affected-zone (CAZ): Defined as "...the depth between the surface and the point internally where the external environment is having virtually no effect on the local humidity regime..." CAZ range is 20-50 mm (0.8-2 in.).

Self desiccation: Defined as "...a reduction of the internal RH with the consequential effects on hydration...." Low water-cement ratio concretes are more prone to self desiccation.

"Plastic shrinkage cracking is perhaps the one defect that in the United Kingdom can be clearly shown to result from inadequate curing procedures, particularly when curing is not applied at a very early age."

It is stated that the "...load-carrying capacity of the structure is the least sensitive property to curing. Conversely, the properties that depend on the outermost skin..., such as weathering or abrasion resistance, will be greatly influenced by...the curing. Between these two extremes lies the zone that governs most of the durability aspects of concrete that cause concern."

"Ponding surfaces with water [in the field] is the closest technique to the 'ideal' laboratory curing."

"Perhaps the best option is to leave the formwork in position for the required curing period. [...] However, this option goes against the 'let's build it fast and cheap' philosophy."

"The whole subject of curing efficiency appears to be very inadequately researched." We need "...a better understanding of the real benefits to be gained from curing. Until we can come to a more considered concept of curing efficiency there is little hope of being able to transfer this properly to on-site applications."

"The actual performance of the concrete needs to be related to both the extent of cement hydration and the curing efficiency in real conditions. Once these are resolved a number of specification routes might become available."

Research needed: Laboratory measurements to include a series of carefully executed comparisons of curing technique and duration against the properties of the concrete considered the most important—compressive strength, ultrasonic pulse velocity, surface hardness, permeability, porosity, and absorption.

For curing efficiency on structure itself—use target hydration state or some property closely related to it. "The target could be set from levels determined in laboratory tests, but more realistically by choosing some proportion of the curing achieved in, say, the centre [sic] of the section, e. g. 'at 15 mm (0.6 in.) depth the curing efficiency (however defined) shall be 85% of that achieved at 150 mm (6 in.) depth'."

Another matter mentioned by the author is "...the fact that curing is not usually a separately billed item and is therefore not costed is considered to be a significant barrier to effective curing on site."

4.26 **GUIDE TO USING SILICA FUME IN PRECAST/PRESTRESSED CONCRETE PRODUCTS, Prepared by PCI Committee on Durability, PCI Journal, Vol. 39, No. 5, September-October 1994, pp. 36-45.**

"Although high performance concrete containing silica fume has often been used successfully in precast, prestressed structural concrete members, it may be desirable only in some applications. Carefully fabricated, finished, and cured precast concrete without silica fume has exhibited excellent performance in typical uses. Silica fume may be added to decrease permeability. Though generally not needed to provide required strength, silica fume may also be added to enhance strength. The increased care and expense needed to produce defect-free high performance concrete containing silica fume may make it more trouble than benefit."

"The purpose of this document is to provide guidelines for consistently producing high performance precast and prestressed concrete containing silica fume that will perform satisfactorily."

"High Performance Concrete—A concrete with or without silica fume having a water-cement ratio of 0.38 or less, compressive strength at or above 55.2 MPa (8,000 psi) and permeability 50 percent lower (by AASHTO T-259 or T-277 methods) than that of conventional mixes."

With silica fume "...there is greater potential for plastic shrinkage cracking."

"There is potential for increased drying shrinkage in the very short term (even overnight for accelerated curing if not protected against moisture loss)."

"For long term shrinkage on properly cured specimens, *replacing* cement with silica fume will not increase shrinkage. But if silica fume is *added* to an unreduced volume of cement in a mix, the higher paste volume will lead to increased shrinkage."

"Effects of Accelerated Curing—When radiant heat is used for curing, it will increase the moisture loss on the exposed surface. This increased loss will be especially critical on members such as double tees with a high surface-to-volume ratio. In addition, accelerated curing has been shown to be very effective in producing high performance at early ages with silica fume. The heat obviously accelerates the pozzolanic reaction. Rates of shrinkage during the accelerated curing may then also be accelerated."

"No matter how well a concrete mix is proportioned, placed, and consolidated, the success of the project will depend on the degree of care taken during finishing and curing."

With regard to concretes containing silica fume, it is recommended that they be over-cured.

"Over-curing means that in order to get the maximum benefit from high performance concrete containing silica fume, curing must be effective and more curing effort must be made compared with conventional concrete in the same placement. Extra curing efforts include maintaining moisture content and temperature to allow desired concrete properties to develop. One important key is that curing must begin directly after finishing. Insufficient curing frequently leads to excessive shrinkage cracking. Curing is not the operation to try to save money."

This report contains the following information on curing:

1. "Concrete, whether it contains silica fume or not, will not perform well unless it is properly cured. This rule is doubly important for high performance concrete containing silica fume—do not expect to achieve high strength or low permeability if the silica fume supplier's guidelines are not followed.

2. [...]Proper curing involves two aspects—maintenance of proper moisture conditions and proper temperature conditions until the desired concrete property levels are developed. The concrete property of lower permeability develops more slowly than does compressive strength. A longer curing time may, therefore, be required to produce a specified low permeability. This extended curing can be accomplished by applying a membrane-forming curing compound or evaporation retarder immediately after removing the hardened concrete from its form.

3. It is recommended that curing of silica fume concrete begin immediately after finishing, whatever the finishing process may be. High dosages of silica fume produce concrete that will not bleed. Therefore, there is no requirement to wait for the bleeding to conclude before initiating curing. A curing compound or evaporation retarder should be applied within a few minutes after final finishing.

4. Silica fume concrete has been successfully cured using most of the generally accepted practices including wet burlap, sheets of plastic, and curing compounds. As with any concrete, the secret is to maintain the curing once it has been initiated. A single cycle of drying can have a significant detrimental effect on the properties of the concrete.

5. If silica fume is used in concrete that will be subjected to accelerated curing, the curing cycle may have to be modified. The concrete must reach an initial set before beginning the accelerated curing. [...]

6. Use the minimum amount of heat during the accelerated curing period necessary to attain the necessary strengths because heat may accelerate shrinkage and drying.

7. Consider the use of Type I cement vs. Type III cement. This change may reduce the rate of early shrinkage.

8. When rapid drying conditions exist, fog-mist exposed surfaces and cover them as quickly as possible.

9. Steam curing should be used.

10. The concrete surface must be protected against moisture loss. Plastic covers on or just inches above the surface have been used successfully. Curing compounds have been used with some limited success. The curing compound's effectiveness will depend on the resulting amount of moisture loss allowed by the particular compound. Consider using a curing compound and plastic covers. Cover quickly after finishing.

11. Minimize temperature differentials between the concrete mass and the ambient air to which the top surface is exposed. Detension strands immediately upon stripping off covers, or develop a way to detension strands before stripping covers (or partially detension before stripping covers). High performance concrete containing silica fume

may mature more rapidly than a conventional concrete. Detensioning should occur as soon as the concrete has developed sufficient strength to accommodate the prestressing forces."

4.27 **Forster, Stephen W., HIGH-PERFORMANCE CONCRETE—STRETCHING THE PARADIGM, Concrete International, Vol. 16, No. 10, October 1994, pp. 33-34.**

High performance concrete is defined as "...a concrete made with appropriate materials combined according to a selected mix design and properly mixed, transported, placed, consolidated, and cured so that the resulting concrete will give excellent performance in the structure in which it will be placed, in the environment to which it will be exposed, and with the loads to which it will be subjected for its design life."

4.28 **Aitcin, Pierre-Claude and Lessard, Michel, CANADIAN EXPERIENCE WITH AIR-ENTRAINED HIGH-PERFORMANCE CONCRETE, Concrete International, Vol. 16, No. 10, October 1994, pp. 35-38.**

This article considered the construction of the Highway 50 Bridge and the Portneuf Bridge, in the province of Quebec.

"In both cases, a 60 MPa (8700 psi) compressive strength measured on 100 x 200 mm (4 x 8 in.) cylinders at 28 days was stipulated and a 1 day compressive strength of 10 MPa (1450 psi) was required to speed up the construction process and to avoid any undue delays."

"In both cases, a blended silica fume cement containing between 7.5 and 8.5 percent silica fume was used, but not of the same brand. The same superplasticizer, air-entraining agent, and retarding agent were used in both cases."

"Since the Portneuf Bridge was built in late October, 1992, with an average daily air temperature of 3 °C (37 °F), it was necessary to heat the mixing water to meet the temperature specification. The Highway 50 viaduct, built in late June, 1993, required replacement of an average of 40 kg (88 lb.) of mixing water with 40 kg (88 lb.) of crushed ice."

Curing—"In both cases, a curing compound was applied to the surface of the concrete as soon as it was finished to prevent any water evaporation. At Portneuf, insulating blankets were placed on the deck as soon as the concrete surface could bear the weight of a worker....

In the case of Highway 50, it was decided to start placing at 4 o'clock in the afternoon and continue non-stop for 16 hours to avoid drying shrinkage problems that could be caused by daylight temperatures. The concrete surface was protected with wet burlap 18 hours after the first load of concrete had been placed. The burlap was sprayed with water over 3 days to provide additional curing and to cool the concrete."

4.29 **Papworth, Frank and Ratcliffe, Royce, HIGH-PERFORMANCE CONCRETE—THE CONCRETE FUTURE, Concrete International, Vol. 16, No. 10, October 1994, pp. 39-44.**

"Using high-strength concrete means that engineers have to design based on recent research data. For example, the current Australian structures code is only relevant for concrete up to 50 MPa (7,300 psi)."

4.30 **MATERIALS FOR TOMORROW'S INFRASTRUCTURE: A TEN-YEAR PLAN DEPLOYING HIGH-PERFORMANCE CONSTRUCTION MATERIALS AND SYSTEMS, Technical Report, Civil Engineering Research Foundation, December 1994.**

Concerning the potential of high-performance concrete, "...denser and less permeable high-performance concrete has the capability to produce lightweight structures with service lives measured in centuries rather than years."

"HPC can be defined as concrete with improved constructability, improved durability, and improved mechanical properties. Unlike conventional concrete, HPC meets one or more of these requirements:

- Places and compacts easier
- Achieves high strengths at early ages
- Exhibits superior long-term mechanical properties such as strength, resistance to abrasion or impact loading, and low permeability
- Exhibits volume stability and thus deforms less or cracks less
- Lasts longer when subjected to chemical attach, freezing and thawing, or high temperatures
- Demonstrates enhanced durability"

The U. S. produces more than 500 million tons of concrete yearly. HPC currently represents no more than perhaps 5-10% of the total concrete placed annually in the U. S.

"The highest strength concretes commercially available today are in the 70 MPa to 100 MPa (10,000 to 15,000 psi) range, with some slightly higher used in building interiors."

The following research need was among those identified for HPC:

Research Topic	Research Project	Objective
Curing for optimum performance	Fundamental parameters affecting Curing of HPC	Develop and implement efficient experimental plan to determine fundamental parameters affecting curing of HPC

4.31 **Dhir, R. K., Hewlett, P. C., Lota, J. S., and Dyer, T. D., AN INVESTIGATION INTO THE FEASIBILITY OF FORMULATING "SELF-CURE" CONCRETE, Materials and Structures, Vol. 28, No. 174, December 1994, pp. 606-615.**

The authors summarize this article as follows: "To achieve good cure, excessive evaporation of water from a freshly cast concrete surface should be prevented. Failure to do this will lead to the degree of cement hydration being lowered and the concrete developing unsatisfactory properties. Curing can be performed in a number of ways to ensure that an adequate amount of water is available for cement hydration to occur. However, it is not always possible to cure concrete satisfactorily. This paper is concerned with achieving optimum cure of concrete without the need for applying external curing methods. The feasibility of curing concrete by adding water-soluble chemicals during mixing that reduce water evaporation in the set concrete, making it 'self-curing' is discussed. The chemicals' abilities to reduce evaporation from solution and to improve water retention in ordinary portland cement was monitored by measuring weight loss. x-ray powder diffraction and thermogravimetry measurements were made to assess whether any improvement in water retention was matched by an increase in degree of cement hydration. Initial surface absorption tests and compressive strength measurements were made to determine surface permeability and strength development, respectively. The scanning electron microscope was used to determine the influence of the admixtures on cement paste microstructure. It was found that two of the chemicals studied had a significant 'self-curing' effect. One of these chemicals enhanced hydration further than simply by means of water retention. A possible explanation of this behaviour [sic] is given."

The explanation by the authors for the one specific chemical enhancing hydration beyond that achieved by water retention alone is that the chemical has the effect of reducing the concentration at which CH begins to come out of solution. This chemical is given the designation A1. To further explain how this happens, the authors state: "Normally CH comes out of solution when its concentration in water reaches a point of supersaturation.... It is possible that chemical A1 has the effect of reducing the concentration at which CH comes out of solution and that consequently the nature of the crystals produced is altered by this change. Lowering the concentration at which CH begins to come out of solution would encourage the further formation of CH. This would explain the improvement in degree of hydration beyond that expected when this chemical is used."

4.32 STATE-OF-THE-ART REPORT ON HIGH-STRENGTH CONCRETE, Reported by ACI Committee 363, ACI Manual of Concrete Practice, 1994, Part 1, Materials and General Properties of Concrete.

Definition of high-strength concrete (HSC):
"The following working definition was adopted: ' The immediate concern of Committee 363 shall be concretes that have specified compressive strengths for design of 41 MPa (6,000 psi) or greater, but for the present time, considerations shall not include concrete made using exotic materials or techniques'."

"The availability of data for higher-strength concretes requires a reassessment of the design equations to determine their applicability with higher-strength concretes. Consequently, caution should be exercised in extrapolating data from lower-strength to high-strength concretes. If necessary, tests should be made to develop data for the materials or applications in question."

"The effect of cement characteristics on water demand is more noticeable in high-strength concretes because of the higher cement contents.

High cement contents can be expected to result in a high temperature rise within the concrete."

"Entrained air has the effect of reducing strength, particularly in high-strength mixtures, and for that reason it has been used only where there is a concern for durability."

"Accelerators are not normally used in high-strength concrete unless early form removal is critical."

Experience indicates "...that concrete incorporating silica fume has an increased tendency to develop plastic shrinkage cracks. Thus, it is necessary to quickly cover the surfaces of freshly placed SF concrete to prevent rapid water evaporation."

"Curing is extremely important in the production of high-strength concrete." After placement and establishment of the paste structure, "...water should be freely available, especially during the early stages of hydration. [...] If the aggregates are capable of absorbing a moderate amount of water, they can act as tiny curing-water reservoirs distributed throughout the concrete, thereby providing the added curing water which is beneficial to these low water-cement ratio pastes."

"High-strength concrete mix proportioning is a more critical process than the design of normal strength concrete mixtures."

"High-strength concretes continue to gain considerable strength above and beyond design requirements with the passage of time, more than lower-strength concretes. While the percentage gain of compressive strength of high-strength concretes from 7 days to 90 days may be equal to or lower than concretes in lower strength ranges, the order of magnitude of strength gain expressed in psi is actually much higher."

"Generally concretes which develop high later-age strengths will also produce high early-age strengths. [...] Early age strengths may be more variable due to the influence of curing temperature and the early-age characteristics of the specific cement."

"When selecting mix proportions, the type of curing anticipated should be considered along with the test age, especially when designing for high early strengths. Concretes gain strength as a function of maturity, which is usually defined as a function of time and curing temperature."

"Water-cementitious [materials] ratios by weight for high-strength concretes typically have ranged from 0.27 to 0.50."

"Common cement contents in HSC test programs range from 392 to 557 kg/m^3 (660 to 940 lb. $/yd^3$)."

"Stickiness and loss of workability will be increased as higher amounts of cement are incorporated into the mixture."

For HSC, "...it is possible that special precautions may be necessary to provide adequate curing water, so that sufficient hydration can occur."

"Although sometimes required, air-entraining agents have been found to be very undesirable in high-strength concretes due the dramatic decrease in compressive strength which occurs when these admixtures are used."

"Need for Curing—Curing is the process of maintaining a satisfactory moisture content and a favorable temperature in concrete during the hydration period of the cementitious materials so that desired properties of the concrete can be developed. Curing is essential in the production of quality concrete; it is critical to the production of high-strength concrete. The potential strength and durability of concrete will be fully developed only if it is properly cured for an adequate period prior to being placed in service. Also, high-strength concrete should be water cured at an early age since partial hydration may make the capillaries discontinuous. On renewal of curing, water would not be able to enter the interior of the concrete and further hydration would be arrested.

Type of Curing—Water curing of HSC is highly recommended due to the low water-cement ratio employed. [...]

Method of Curing—As pointed out in ACI 308, the most thorough but seldom used method of water curing consists of total immersion of the finished concrete unit in water. 'Ponding' or immersion is an excellent method wherever a pond of water can be created by a ridge or dike of impervious earth or other material at the edge of the structure. Fog spraying or sprinkling with nozzles or sprays provides satisfactory curing when immersion is not feasible. [...] Burlap, cotton mats, rugs, and other coverings of absorbent materials will hold water on the surface, whether horizontal or vertical. Liquid membrane-forming curing compounds retain the original moisture in the concrete but do not provide additional moisture."

This report mentions that "...several investigators have suggested that the specification for compressive strength should be modified from the typical 28-day criterion to either 56 or 90 days."

"Curing concrete test specimens at the construction site and under job conditions is sometimes recommended since this is considered more representative of the curing applied to the structure. Tests of job-cured specimens may be highly desirable and are necessary when determining the time of form removal, particularly in cold weather, and when establishing the rate of strength development of structural members."

"High-strength concrete shows a higher rate of strength gain at early ages as compared to lower-strength concrete but at later ages the difference is not significant...."

"Special attention should be paid to the testing of high-strength concrete cylinders since any deficiency will result in an apparent lower strength than that actually achieved by the concrete. Items deserving specific attention include manufacture, curing, and capping of control specimens for compressive strength measurements; characteristics of testing machines; type of mold used to produce specimens; and age of testing."

4.33 **Aitcin, P. C., DURABLE CONCRETE—CURRENT PRACTICE AND FUTURE TRENDS, Concrete Technology: Past, Present, and Future, Proceedings of V. Mohan Malhotra Symposium, SP-144, American Concrete Institute, Detroit, 1994, pp. 85-104.**

This article deals with many of the current issues concerning high strength/high performance concrete. The importance of proper curing is emphasized throughout the article.

"From the materials standpoint, concrete durability is closely linked to concrete microstructure, more specifically to its impermeability."

"Recent studies show that concrete mixtures for use in severe environments can be made essentially impermeable to air, water, and chloride ions if they possess a minimum of 50 MPa (7,250 psi) compressive strength at 28 days."

"In addition to specifying the proper concrete mixture having an adequate water/cement ratio for the given environment, it is essential to insure that the concrete is properly cast and cured to secure good durability."

The author states that "...durability is...affected by the care with which the concrete is initially placed and cured. A good concrete mixture used in a sound design can have its durability severely impaired by improper placement and curing. This is a particularly noticeable drawback of concrete when compared to other construction materials."

"Early desiccation can be disastrous for durability because it creates a network of fissures on exposed surfaces through which aggressive agents can attack the concrete. Unfortunately, the early curing of freshly-cast concrete is often neglected because it slows down the construction process. Contractors have been too often reluctant to invest enough time and money in such a trivial thing as spraying some water on freshly-cast surfaces or adopting adequate means to prevent water evaporation from exposed surfaces. And yet curing is so critical from a durability point of view. A well-cured concrete surface will exhibit minimal cracking, while the concrete that dries very rapidly will be weakened forever and can permit aggressive agents to penetrate easily."

"For many years, it was impossible to reduce the water/cement ratio of concrete below 0.40. Even the most efficient water reducers used in the concrete industry were not able to sufficiently deflocculate cement particles. This situation changed with the advent of superplasticizers. During the last two decades, it was realized that the strong deflocculating properties of superplasticizers could be advantageously used to drastically lower the water/cement ratio...[as low as 0.25 and, in some cases, even as low as 0.20]. [...] This technological breakthrough has resulted in the development of a new family of high-strength concrete which is now increasingly referred to as high-performance concrete.

In most of these new low water-cement ratio concretes, there is not enough water available to fully hydrate all of the cement. Therefore, when hydration stops from a lack of water, concrete still contains some unhydrated cement particles. These unhydrated particles can play an important role since they constitute strength in a reserve as in older concretes. If for any reason, structural or environmental, concrete becomes cracked, unhydrated cement particles begin hydrating as soon as water starts to penetrate the concrete. This means that unhydrated cement particles offer some self-healing potential. However, a potential for expansion and cracking exists if concrete is inadequately restrained."

The author says, "...the use of the new generation of concrete called HPC, which has already gained acceptance within the construction industry, will become more prevalent in the future. The reduction in the water/cement ratio in this type of concrete not only leads to higher strength, but also improved durability."

"Large surfaces of high performance concrete will crack very rapidly and deeply if they are not properly cured. As high performance concrete has a low water/binder ratio, is not prone to bleed, and its surface is very sensitive to plastic shrinkage cracking. Therefore, appropriate measures must be taken to prevent plastic shrinkage cracking."

"When engineers will realize that concrete must no longer be specified in terms of compressive strength but rather in terms of its water/cement ratio, they can then begin to minimize durability problems. They will have, however, to make sure that this potentially durable concrete is adequately cast and cured."

4.34 **Ayers, M. E. and Khan, M. S., OVERVIEW OF FLY ASH AND SILICA FUME CONCRETE: THE NEED FOR RATIONAL CURING STANDARDS, Concrete Technology Past, Present, and Future, Proceedings of V. Mohan Malhotra Symposium, SP-144, ACI, Detroit, 1994, pp. 605-622.**

"The curing requirement of fly ash and silica fume concretes is identified as one of the important areas that need further investigation to utilize the full potential of these concretes." A reasonable amount of data exists in the literature on the curing requirements of fly ash concretes; however, very limited data exists on curing requirements for silica fume concrete. Confusion exists in the construction industry on the curing of silica fume concrete.

The authors state that high strength concrete and silica fume concrete have become synonymous. The modulus of elasticity, E, increases with the addition of silica fume.

"In general, the lower the rate of strength development [for fly ash concretes], the longer the concrete needs to be maintained at a satisfactory moisture content and temperature."

Studies have shown "...that fly ash concretes are more susceptible to substandard curing conditions than plain cement concrete."

This article notes that "...ACI Committee 308 report 'Standard Practice for Curing Concrete'...does not address the curing of any pozzolanic concrete including fly ash concrete and silica fume concrete."

"In the absence of standard specifications, the experts on silica fume concrete have acted conservatively on the curing issue, and advocated overcuring...."

4.35 **STANDARD PRACTICE FOR CURING CONCRETE (ACI 308-92), Reported by ACI Committee 308, ACI Manual of Concrete Practice Part 2---- 1994.**

"Curing is the maintaining of a satisfactory moisture content and temperature in concrete during its early stages so that desired properties may develop." Curing requirements for high performance concrete (HPC) are not given. Curing develops strength and durability.

Two methods (systems) for maintaining satisfactory moisture content—water curing and sealing materials.
Minimum curing requirements:

- TYPE II cement—14 days
- TYPE I cement—7 days
- TYPE III cement—3 days
- Keep moist at temperature >10 °C (50 °F)

4.36 **Hilsdorf, H. K., CONCRETE STRUCTURES EURO-DESIGN HANDBOOK, Concrete Section, 1994/96, OFFPRINT.**

This is a section on concrete from a handbook which has been prepared in connection with the new European standards.

This publication contains guidelines and recommendations on the curing of concrete. Some of this material on the curing of concrete is described below.

"The methods of curing may be subdivided into two categories: methods where water is added and methods which prevent or retard the rate of drying of the concrete. Methods of the first category are, e.g., sprinkling of water on the concrete surface or submerging the concrete element in water. Methods of the second category are, e.g., keeping the formwork in place, covering the concrete surface with plastic films, placing of wet coverings or applying curing compounds which form protective membranes. These methods may be applied individually or in combination. Generally, those methods where water is added, are more effective than the methods which prevent or retard drying."

"Liquid curing compounds should be applied on the entire concrete surface as soon as possible, e.g., after the concrete surface has lost its sheen, or after completion of the final finishing procedures."

"The required duration of curing depends primarily on the following parameters:

- The curing *sensitivity* of a particular concrete. It depends in turn on the composition of the concrete, in particular on the type and strength class of the cement as well as any additions. Concretes made of slowly hydrating cements with a high percentage of compounds other than portland cement clinker, as well as concretes with large amounts of pozzolanic additions, generally are more curing sensitive than concretes made of portland cements, because of their slower rate of hydration. Concretes with low water/cement ratios tend to hydrate somewhat slower than concretes with higher water/cement ratios. However, if the impermeability of the concrete at the end of curing is the criterion in setting up the required duration of curing, then concretes with a low water/cement ratio need less curing than concretes with a higher water/cement ratio since they reach a given level of impermeability sooner.

- The *concrete temperature* [is another factor]...the rate of hydration of cements decreases substantially with decreasing temperature. Therefore, an increase of the duration of curing is mandatory if the concrete temperature is significantly less than 20 °C (68 °F). [...] The effect of temperature on the required duration of curing can be estimated reliably from the maturity functions.... This, however, requires continuous monitoring of the concrete temperature in the surface layers of a structural concrete member. [...]

  In cases, where curing of concrete is of particular importance, the effects of type of cement, additions and admixtures on the activation energy and thus the temperature dependence of cement hydration should be taken into account. [...]

- The *environmental conditions* during and immediately after curing of the concrete. High temperatures, sunshine and high winds accelerate the rate of drying of the young concrete. Under such conditions, the concrete should be cured for prolonged periods of time, because otherwise the concrete will dry out rapidly after curing, so that the hydration of the surface near regions will rapidly come to an end. If, however, the relative humidity of the surrounding environment is high, even the near surface regions of a concrete section may continue to hydrate for quite some time after termination of curing.

- The *exposure conditions* of the structural member during its service. The more severe these conditions, the longer the required curing time in order to ensure sufficient durability of the concrete."

"One of the problems in setting up rules for the duration of curing, is the choice of a suitable criterion for the duration of curing. Criteria which have been discussed are: the effect of curing on progress of carbonation, a required impermeability of the concrete cover at the end of curing, a certain minimum compressive strength of the concrete at the level of the reinforcement, and practical experience, i.e., service records of concrete structures which showed no signs of deterioration after many years and for which the applied curing conditions are known. The latter criterion in combination with permeability requirements have been chosen for the durations of curing proposed in ENV 206: with respect to curing, concrete is classified on the basis of its strength development which may be rapid, medium or slow...." The minimum required duration of curing in days "...depends on the strength development of the particular concrete, on the ambient conditions during curing and on concrete temperature: the duration of curing increases as the rate of strength development of the concrete decreases, as the concrete temperature decreases and as the environmental conditions during curing—as an indicator of the conditions to be expected immediately after curing—lead to higher rates of drying of the concrete." Alternative approaches to curing based on maturity considerations may also be taken into account.

Since experience has shown it is sometimes difficult to implement the curing requirements in ENV 206, these provisions are being reconsidered. "Since curing of concrete, in despite of its significance for the durability of concrete structures, is neglected in many countries, it has been proposed repeatedly to list curing of concrete as a separate item in construction contracts."

"The requirements for curing of high-strength concretes generally correspond to those for conventional concretes. Curing methods where water is added are to be preferred, because in high-strength concrete the mixing water is used up rapidly by hydration, leading to self desiccation and the corresponding shrinkage of the cement paste. However, in this context it should be kept in mind, that high-strength concretes become so impermeable after a few days of hydration, that the rate of water penetration is very slow, and water supplied by curing cannot penetrate sufficiently and thus does not contribute to further hydration."

4.37 **Torii, K. and Kawamura, M., MECHANICAL AND DURABILITY-RELATED PROPERTIES OF HIGH-STRENGTH CONCRETE CONTAINING SILICA FUME, High-Performance Concrete, Proceedings, ACI International Conference, SP-149, Singapore, 1994, pp. 461-474.**

This paper "...presents the data on the effects of silica fume on mechanical and durability related properties of high-strength concrete. High-strength concrete had a compressive strength of the range of 90 to 100 MPa (13,000 to 14,500 psi)."

"Durability related properties such as the chloride ion permeability, the resistance to freezing-thawing and the depth of carbonation of high-strength concrete with and without silica fume were also investigated with a special interest on the influence of curing condition at early ages on their properties." Tests showed "...the resistance of non-AE [air-entrained] high-strength concrete with and without silica fume to the freezing and thawing cycles was very sensitive to the lack of moist curing at early ages, and a poorly cured non-AE high-strength concrete containing 8 % silica fume deteriorated more seriously."

In high-performance concrete "...the curing condition at early ages seems to be an important factor to ensure a high-strength and durability of concrete because high-strength concrete with a low water-cement ratio is liable to self-desiccate. However, there are relatively few studies concerning the influence of curing condition at early ages on the pore structure and permeability of high-strength concrete with and without silica fume."

The study presented in this paper considered the effects of curing condition at early ages on durability related properties such as chloride ion permeability, resistance to freezing-thawing, and depth of carbonation of high-strength concrete with and without silica fume.

"Cylindrical concrete specimens, 100 mm (4 in.) in diameter and 200 mm (8 in.) in height, were prepared. Concrete specimens for the compressive and splitting tensile strength test were cured in water for the prescribed time of 3, 7, 14, 28 and 91 days. Curing regimes of concrete specimens for the measurements of durability related properties were as follows; they remained 24 hours in the moulds [sic] placed in the moist room at 20 °C (68 °F), then demoulded [sic] and stored in the water at 20 °C until the ages of 3, 7 and 14 days when they were moved to the dry room at 20 °C and 60% r.h. where they remained until the age of 28 days. [...] Concrete specimens which were successively stored in a room maintained at 20 °C and 60% r.h. or in water at 20 °C for 28 days were also prepared...."

"After various initial curing regimes for 28 days, concrete specimens were exposed to the dry environment at 20 °C (68 °F) and 60% r.h. for about 1 year, where the concentration of carbon dioxide gas in the atmosphere was 0.084%. The depth of carbonation of concrete was determined by spraying a 1% phenolphthalein ethanol solution containing 10% water on the surface of split concrete specimens."

Regarding pore size, "...the difference in pore size distributions between normal- and high-strength concrete well cured and poorly cured was showed up more distinctly in the coarse pores larger than 0.1 μm (0.4 x 10^{-5} in)." The influence of poor curing conditions on the pore structure of high-strength concrete was not as significant as it was in normal-strength concrete. The authors conclude that "...the formation of a dense and homogeneous pore structure in high-strength concrete containing 8% silica fume at early ages seems to be one of the main factors contributing to the development of 28-day compressive strength of around 90 MPa (13,000 psi)."

"Normal-strength concrete with and without silica fume rapidly deteriorated at early repetitions of freezing and thawing, which showed a relatively large amount of scaling in all curing regimes. On the other hand, the freezing-thawing resistance of high-strength concrete with and without silica fume was improved to some extent when compared to normal-strength concrete." It is clear that "...poor curing procedures prior to the repetitions of freezing and thawing are very detrimental to the freezing-thawing resistance of high-strength concrete as well as normal-strength concrete. For high-strength concrete with and without silica fume which was cured in dry environment or moved to dry environment at early ages, there occurred some visible cracks in parallel to the edge of the specimens at the repetitions of freezing and thawing of around 100 cycles, followed by rapid deterioration due to the extension of these cracks."

"The depth of carbonation of normal-strength concrete with and without silica fume increased with decreasing the initial curing time in water at early ages, although normal-strength concrete with and without silica fume showed no carbonation only when they were successively cured in water for 28 days.... On the other hand, all high strength concrete with and without silica fume showed no carbonation in the curing regimes except for the curing condition in dry room for 28 days..., because they had a dense pore structure sufficient to prevent the ingress of CO_2 gas into the concrete."

Some of the major results reported in this article are:

- "High-strength concrete containing 8% silica fume had a dense and homogeneous pore structure independent of curing condition at early ages because of its low water-cement ratio and early progression of pozzolanic reaction of silica fume, resulting in an improvement of compressive and splitting tensile strength at early ages."

- "The influence of poor curing regimes on the chloride ion permeability of high-strength concrete containing silica fume was...very small."

- "High-strength concrete with and without silica fume showed a good resistance to freezing and thawing when it was well cured in water. However, high-strength concrete with and without silica fume rapidly deteriorated during early repetitions of freezing and thawing when it was poorly cured."

- "High-strength concrete with and without silica fume showed no carbonation in the storage of dry environment at 60% r.h. for 1 year. The influence of 8% silica fume replacement on the carbonation depth of concrete was not significant in both normal- and high-strength concrete."

4.38 **Ravindrarajah, R. Sri, Mercer, C. M., and Toth, J., MOISTURE-INDUCED VOLUME CHANGES IN HIGH-STRENGTH CONCRETE, High-Performance Concrete, Proceedings, ACI International Conference, SP-149, Singapore, 1994, pp. 475-490.**

"This paper reports the moisture-induced shrinkage and swelling of high-strength concrete with 28-day cube strengths ranging from 81 to 107 MPa (11,750 to 15,500 psi). [...] The results showed that after 460 days of air-drying, shrinkage of high-strength concretes with 3-day water-curing is between 545 and 775 microstrain, depending on the binder materials used. [...]

Drying shrinkage after 100 days for concretes, which are water-cured for 460 days prior to drying, ranged from 39% to 67% of the corresponding shrinkage for similar concretes which are initially water-cured for only 3 days. [...] The effect of partially replacing the ordinary portland cement with silica fume decreased or increased the shrinkage of concrete, having 3-day water-curing, depending on the silica fume content. However, the shrinkage of concrete, having 460 days of water-curing, decreased when the ordinary portland cement was replaced partially with silica fume up to 15% or with 5% silica fume and 5% fly ash."

"Since most specifications for high-strength concrete require the desired compressive strength at 56 or 90 days, instead at the conventional age of 28 days, it is possible to replace a proportion of portland cement with slow reacting supplementary cementing materials, such as fly ash, and ground granulated blast-furnace slag. Since the presence of water is essential for the reactions of these materials, the curing conditions influence the properties of high-strength concrete containing these materials."

"This paper reports the results of an experimental investigation into the development of drying shrinkage of high-strength concretes with time as affected by the types of binder materials used and the length of initial water curing period. The shrinkage tests were carried out up to 460 days and swelling of preshrunk high-strength concretes was monitored when the test specimens were placed in water."

"The shrinkage specimens were cured in water for either 3 days or 460 days, before they were allowed to dry in the laboratory conditions. The mean temperature and relative humidity of the drying environment were 20 °C (68 °F) and 65%, respectively. The specimens that had an initial water curing for 3 days were placed in water, after 460 days of drying and swelling strains were measured over a period of 55 days. The moisture-induced strains were measured over a gauge length of 200 mm (8 in.) on two opposite sides on each specimen with a demountable mechanical strain gauge."

Some of the major conclusions are as follows:

- "Drying shrinkage after 460 days for high-strength concretes with 3 days of water-curing is between 545 and 775 microstrain, depending upon the combination of the binder materials used."

- "The incremental drying shrinkage between 28 and 460 days for the high-strength concretes ranged from 215 to 285 microstrain."

- "Recoverable shrinkage for high-strength concrete is between 57% and 69% of the total shrinkage."

- "Shrinkage of high-strength concretes at 100 days with 460 days of water-curing was between 39% and 67% of the corresponding shrinkage when the water-curing period was 3 days."

- "The effect of partially replacing the cement with silica fume reduced or increased the shrinkage of concrete, which had the initial water-curing for 3 days, depending on the silica fume content."

- "For the high-strength concrete which had 460 days of water-curing, 15% silica fume in the binder reduced the 100-day shrinkage by 29%, whereas 5% silica fume with 5% fly ash in the binder reduced the shrinkage by 38%."

4.39 **Sakai, K. and Watanabe, H., HIGH-PERFORMANCE CONCRETE: LOW-HEAT AND HIGH-STRENGTH, High-Performance Concrete, Proceedings, ACI International Conference, SP-149, Singapore, 1994, pp. 243-268.**

"Basic studies were conducted to develop high performance concrete, with low-heat and high-strength characteristics under low-temperature environments, using blast-furnace slag. The purpose of this study was to clarify the effects of slag fineness, slag content, gypsum content, limestone-powder content, and high-range water-reducing admixtures (HRWRA) on the strength development, adiabatic temperature rise, porosity, amount of $Ca(OH)_2$, and carbonation of concrete; and the effect of curing temperature on concrete strength development."

Large-scale construction projects are now constructed year-round in many parts of Japan. "This requires concrete not only with low heat, but also with high strength under low temperature environments. In general, these demands are contradictory. Therefore, there has been an extremely small number of studies conducted on low-heat and high-strength concrete...."

The mixture used in this study was a water-cement ratio of 0.40 and a sand-coarse aggregate ratio of 43%. "As much HRWRA as possible was added, to the limit of segregation of the concrete."

"The dimensions of specimens for compressive strength tests were ϕ 100 x 200 mm (4 x 8 in.). The curing temperatures of the specimens were 5 °C (41 °F), 10 °C (50 °F), and 20 °C (68 °F). Those at 5 °C (41 °F) or 10 °C (50 °F) were in sealed conditions for two days immediately after their production, until being removed from their molds; those at 20 °C (68 °F) were moist-cured for one or two days. Afterward, in all cases, the specimens were cured in water until the time of testing."

"The dimensions of specimens for carbonation tests were ϕ 150 x 300 mm (6 x 12 in.). The specimens were moist-cured for 48 hours at 20 °C (68 °F), demolded, and cured in water at 20 °C (68 °F) until the testing age of 28 days."

Some of the major conclusions are:

- "When curing temperatures were 5 °C (41 °F) and 10 °C (50 °F), it was possible to remarkably increase strength at the age of 91 days as well as at early ages by increasing slag fineness.

- As slag fineness became greater, fine pores increased, and coarse pores decreased. However, when gypsum content increased, fine pores decreased and coarse pores increased. The increase of slag fineness and gypsum content resulted in more fine and coarse pore structures, respectively.

- As slag fineness increased, the compressive strength increased.
- As slag content increased, the compressive strength tended to be slightly higher at the age of 3 days, but decreased at and after the age of 28 days.
- Carbonation depth increased as slag content and gypsum content increased."

4.40 **HIGH PERFORMANCE CONCRETE: PROPERTIES AND APPLICATIONS, Edited by S. P. Shah and S. H. Ahmad, McGraw-Hill, Inc., 1994, pp. 17-23 and 35-40.**

High strength concrete "...is not at all a forgiving material. Thus, to ensure the quality of high strength concrete, every aspect of the concrete production must be monitored, from the uniformity of the raw materials to proper batching and mixing procedures, to proper transportation, placement, vibration and curing, through to proper testing of the hardened concrete."

For high strength concretes "...it has become common to determine compressive strengths at 56 days, or even 90 days. [...] It is...perfectly reasonable to measure strengths at later ages, and to specify the concrete strength in terms of these longer curing times."

"In general, the highest concrete strengths will be obtained with specimens continuously moist cured (at 100% relative humidity) until the time of testing."

With respect to type of mold, "...more flexible molds will [generally] yield lower strengths than very rigid molds, because the deformation of the flexible molds during rodding or vibration leads to less efficient compaction than when using rigid molds." It is recommended that rigid steel molds be used whenever practicable, particularly for concrete strengths in excess of about 98 MPa (14,000 psi).

"For most materials, including concrete, it has generally been observed that the smaller the test specimen, the higher the strength. For high strength concrete, however, though this effect is often observed, there are contradictory results reported in the literature." The results of a number of studies have shown the observed strength ratios of 100 x 200 mm (4 x 8 in.) cylinders to 150 x 300 mm (6 x 12 in.) cylinders range from about 1.1 to 0.93. "These contradictory results may be due to differences in testing procedures amongst the various investigators."

With respect to end conditions, "...if the strength of the end cap is less than the strength of the concrete, the compressive load will not be uniformly transmitted to the specimen ends, leading to invalid results. Thus, for high strength concrete, in addition to high strength capping compounds, a number of other end preparation techniques are being investigated. These include grinding the specimen ends, or using unbonded systems, consisting of a pad constrained in a confining ring which fits over the specimen ends." Grinding of the specimen ends is recommended for very high strength concretes.

Best information available at this time is that "...below about 98 MPa (14,000 psi), a thin, high strength sulfur mortar cap may be used successfully. Beyond that strength..., grinding specimen ends is currently the only way to ensure valid test results."

"The strength development with time is a function of the constituent materials and curing techniques. An adequate amount of moisture is necessary to ensure that hydration is sufficient to reduce the porosity to a level necessary to attain the desired strength. Although cement paste will never completely hydrate in practice, the aim of curing is to ensure sufficient hydration. In pastes with lower w/c ratios, self-desiccation can occur during hydration and thus prevent further hydration unless water is supplied externally."

Tests have shown that "...condensed silica fume concrete is more sensitive to curing temperature than ordinary portland cement concrete."

"Curing techniques have significant effects on the strength of concrete. The key concerns in curing, especially for concrete of higher strengths, are maintaining adequate moisture and temperatures to permit continued cement hydration. Water curing of higher strength concrete is highly recommended due to its low w/c ratio. At w/c ratio below 0.40, the ultimate degree of hydration is significantly reduced if free water is not provided. The effects of two different curing conditions on concrete strength were investigated. The two conditions were moist curing for seven days followed by drying at 50% relative humidity until testing at 28 days, and moist curing the 28 days followed by drying at 50% relative humidity until testing at 95 days. Higher strength concrete showed a larger reduction in compressive strength when allowed to dry before completion of curing."

NOTE: Items numbered 4.41 through 4.47 below are from the **THIRD INTERNATIONAL CONFERENCE ON THE DURABILITY OF CONCRETE,** ACI SP-145, American Concrete Institute, 1994.

4.41 **Hasni, L., Gallias, J. L., and Salomon, M., INFLUENCE OF THE CURING METHOD ON THE DURABILITY OF HIGH PERFORMANCE CONCRETES, pp. 131-155.**

"In spite of the very good resistance of high performance (HP) concretes in the presence of aggressive agents, ...the microstructure of the surface concrete can be greatly disturbed by the curing method thereby compromising the durability of the concrete covering the reinforcement.

This paper...[presents] the results of a study bearing on three concrete design mixtures (one reference concrete and two HP concretes with and without silica fume) each subjected to three curing methods

- 100% R.H.; T = 20 °C (68 °F) for 50 days
- Ambient laboratory conditions (50 ± 10 % R.H.; 30 °C (86 °F)) for 50 days
- Desiccation by subjecting to a hot air flow 7 hrs per day for 50 days and the following durability tests:
    - Carbonation and reduction in alkalinity
    - Permeability to chloride ions under imposed electrical potential
    - Microcracking, microporosity, micro-structure."

The reference concrete contained no additives and had a water-cement ratio of 0.55.

"The results concerning carbonation, variation in free lime and microcracking show that HP concrete with silica fume is more sensitive to the curing method than the reference concrete and the concrete without silica fume, as revealed by increased carbonation and a bigger reduction in alkalinity. The study of microcracking in the different concretes showed that desiccation causes more microcracking in the HP concrete with silica fume than in the HP concrete without silica fume."

The authors state that "...many instances of applications of HP concretes, show that the surface microstructure of HP concretes could be greatly disturbed by the curing method and that this might compromise the improvements in durability achieved in the core concrete covering the reinforcements: particularly due to carbonation and penetration by chloride ions, the main mechanisms which initiate corrosion of the reinforcement....

This paper discusses microcracking and the microstructure of the concrete covering the reinforcement in HP concretes depending on the curing method used, these criteria being studied in connection with their influence on durability and problems of corrosion of the reinforcement."

Results show "...that the strengths of HP concrete with silica fume...and of the reference concrete...are more sensitive to a dry curing procedure then the HP concrete without silica fume...."

No shrinkage occurred due to natural desiccation in any of the concretes in the 100% RH environment.

"For all three concretes, dimensional variations reflecting desiccation shrinkage show that the drier the curing method the more pronounced is the phenomenon."

Results were "...that the HP concrete with silica fume is more sensitive to the effect of curing than the HP concrete...without silica fume."

Tests show "...the higher the porosity value at humidity saturation, the more pronounced is the effect of curing, which results in increased porosity."

The authors state "...the more dense is the paste, the less sensitive it is to a variation in porosity after a dry curing procedure. Indeed, the lower the porosity, the less hydrous exchanges will take place."

For the high performance concretes tested, there was very good contact between the paste and the aggregate, low porosity generally and a dense, even structure with the customary presence of cement hydrates.

"Compared to the HP concretes, the reference concrete is fairly compact but shows many more vacuoles and also a fair number of gaps at the paste/aggregate interfaces...."

"The surface microstructure of the concretes is strongly influenced by the curing method.

For the reference concrete and the HP concrete without silica fume, curing results in the gradual appearance of lime and carbonation calcite dissolution facies [sic] as the curing method becomes dryer.... However, neither more extensive microcracking nor any increase in paste/aggregate interface type defects were found with the damp saturation procedure compared to dry curing procedures...."

It was shown "...that the effect of a desiccating procedure is more pronounced for the HP concrete with silica fume than for the HP concrete without silica fume."

For all the concretes, the dryer the curing method, the deeper the effects of carbonation.

The authors state that "...the test of permeability to chloride ions carried out on each concrete did not reveal any increased permeability in the concretes with the damp saturated method compared to the dry methods. However, the differences in permeability found in the HP concretes compared to the reference concrete distinctly correlate with... the compactness of the different concretes."

"With the damp curing method {100% RH, 20 °C (68 °F)} the dynamic modulus and the pulse velocity of the HP concretes are higher than those of the reference concrete thereby indicating better bonding in the HP concrete than in the reference concrete."

The authors found "...that HP concretes have good contact between paste and aggregate, low porosity and a dense, even texture whereas the reference concrete although fairly compact includes many more voids at the paste/aggregate interfaces.

However, the microstructure of the concretes at the surface is influenced by the curing method, especially the HP concrete with silica fume."

The article explains "...that although the HP concrete without silica fume shows less carbonation than the reference concrete and the HP concrete with silica fume, its carbonation after 21 days of a very dry curing procedure nevertheless reached a value of 10 mm (0.4 in.)."

The HP concrete "...with silica fume carbonates more than the reference concrete... subjected to the same curing methods.

Generally speaking, it was found that the HP concrete containing silica fume is more sensitive to the influence of curing than the HP concrete without silica fume although they had identical compressive strengths {90 MPa (13,000 psi)} at 50 days when cured under the damp saturated procedure...."

The HP concrete without silica fume has a slightly more dense paste than the HPC with silica fume "...as confirmed by the microstructural inspection carried out after the damp curing method {100% RH, 20 °C (68 °F)}."

"Curing has the effect of considerably reducing the compactness of the HP concrete with silica fume compared to the HP concrete without silica fume."

"This study illustrates the extreme importance of surface effects and the need to take the curing method into account as it affects the microstructure and microcracking of the cover concrete and these parameters govern the durability of the cover concrete with respect to carbonation and penetration by chloride ions in the presence of any other phenomenon involving exchanges with the exterior milieu [sic]."

4.42 **Marsh, B. K. and Ali, M. A., ASSESSMENT OF THE EFFECTIVENESS OF CURING ON THE DURABILITY OF REINFORCED CONCRETE, pp. 1161-1176.**

"Specifications for curing in standards and codes of practice vary considerably from nation to nation and are rarely based directly on durability-influencing parameters such as permeability and sorptivity. Many of these specifications date from a time when the deterioration mechanisms of reinforced concrete were not well understood and, because of that, are based largely on strength development. It is also probably true to say that strict adherence to these specifications in practice, especially for vertical surfaces, is the exception rather than the rule. In a survey of 30 contracts...involving vertical pours, 13 applied no curing at all. Overall, it was judged that in very few cases were the methods adopted sufficiently thorough to ensure full compliance with the specification. It is interesting that in the same study it was found that for the 33 slab or pavement contracts surveyed only 3 applied no curing.

Much has been said on the importance of curing for *all* concrete...yet the published literature is sadly lacking in technical quantification of the effects of curing in practice, especially for formed surfaces. Poor curing or lack of curing has been blamed for premature deterioration of structures but, in the case of carbonation-induced corrosion of reinforcement, this view must be regarded as largely speculative. It is rarely, if ever, possible to establish a firm link between the actual curing that the concrete experienced and the rate of deterioration. Crucial factors that must be taken into account are the composition of the concrete, whether it achieved full compaction, and the cover to the reinforcement. Indeed a recent joint study of over 400 structures by the Building Research Establishment and the British Cement Association has confirmed inadequate cover as the most influential factor in premature deterioration of reinforced concrete structures....

In...this paper, curing is taken to mean the provision or preservation of a moist environment to reduce the rate of loss of water from the concrete; no deliberate attempt was made to control the temperature other than simulation of different ambient temperatures at the time of casting. The study was aimed at structural concrete, cast in-situ against formwork, in buildings in temperate climates where carbonation-induced corrosion of reinforcement is the most likely cause of deterioration. It was limited to concrete cast in plywood formwork and protected by this formwork for at least the first 16 hours after casting. The results of this work may thus not apply to unformed surfaces such as slabs, certain precast products, hot or very cold climates or situations where freezing and thawing, abrasion or chloride-induced corrosion are the most likely causes of deterioration. The use of curing membranes was not included in this study."

"A comprehensive review of attitudes and practices of site curing of concrete in 1981... showed that, although the prime reason for curing was considered to be the retention of moisture to ensure maximum hydration, there was a low awareness of the relevance of curing to permeability and porosity. Much more prominent was the belief that curing was important to obtain the maximum strength.

Much of the work that has established and continues to support the perception of the importance of curing has been based on tests on laboratory specimens that have been stored in water for different periods of time. Such tests have generally shown the importance of curing in improving properties such as strength, impermeability...and resistance to carbonation.... Much less work can be found on tests on in-situ concrete or large-scale laboratory specimens cured by the methods common in practice."

The authors note that "...exposure test results...show that even for outdoor exposure, sheltered from rain, the depth of carbonation of the concrete, after approximately four years, is largely unaffected by a range of curing regimes from poor (no curing) to very good (seven days in wet hessian). For an in-situ test to be truly effective in predicting the performance of the concrete in service it needs to measure a suitable property of the concrete itself, independently of its moisture content." For the study presented in this paper, "...where carbonation-induced corrosion of reinforcement is the prime concern, permeability to gas would probably be suitable."

The article closes with conclusions:

"The following conclusions are based on studies of the effect of curing on the durability of structural concrete, cast in formwork, in a temperate climate where the most likely cause of deterioration is carbonation-induced corrosion of reinforcement. They do not necessarily apply to unformed concretes, concretes subject to abrasion, freezing and thawing, or exposure to chlorides, or concretes cast in hot climates.

1. Normal variability within concrete may be greater than the measurable effect of common practical curing methods.

2. Curing by methods by which free water is applied to the concrete surface are generally more effective than methods that aim to prevent or limit moisture loss.

3. Measurements of the effect of curing on penetrability properties of concrete made on small specimens do not compare well with those obtained from larger scale specimens that are more representative of cast in-situ concrete construction.

4. Compressive strength of concrete away from the surface in a structure is not very sensitive to curing.

5. Little evidence was found, from a range of test methods, of easily measurable effects of practical curing on durability related properties of concrete after removal of formwork except in conditions of very dry air."

4.43 **Austin, S. A., Robins, P. J., and Al-Eesa, A. S. S., THE INFLUENCE OF EARLY CURING ON THE SURFACE PERMEABILITY AND ABSORPTION OF SILICA FUME CONCRETE, pp. 883-900.**

This article reports on part of a substantial research program on the properties of condensed silica fume concretes cured in temperate and hot climates.

"Producing strong and durable concrete in a hot arid climate can be considerably more difficult than in a temperate one. In particular, inadequate curing can result in early age cracking or porous and permeable concrete, which in turn produces structures which are then prone to reinforcement corrosion and other processes of degradation. This has led to an interest in the potential for the use of alternative cementitious materials and appropriate curing methods to improve concrete quality in hot climates.

The use of cement replacements (ground granulated blast furnace slag, GGBS, and condensed silica fume, CSF) in hot climates has been investigated...with an emphasis on curing methods, replacement levels and durability related properties as well as strength...."

"The research on silica fume concretes has concentrated on the effects of both curing method and duration on the development of strength and permeability of concretes with varying levels of silica fume. This paper concentrates on the influences of early curing on the surface permeability of normal portland cement concretes and silica fume concretes with a 10% replacement level, designed for equal 28 day water-cured strengths.

In order to obtain good concrete the placing of an appropriate mixture must be followed by adequate curing in a suitable environment during the early ages of hardening. Curing problems are exaggerated when concreting in hot weather due to both higher concrete temperatures and increased rate of evaporation. The durability, strength, and other characteristics of concrete in hot climates are thus critically dependent on its treatment during the first few weeks from the moment it is compacted. Inadequate curing can negate all the earlier care taken in mixture design and concreting operations, and can also lead to serious defects such as plastic shrinkage cracking and excessive drying shrinkage."

"There appears to be little published data on the influences of curing on the permeability/absorption of silica fume concretes. There is also relatively little information on the performance of silica fume concretes in hot environments. For moist-curing at 20 °C (68 °F), the authors have found that the early-age strength development of a CSF concrete is slower than a normal portland cement control concrete of equal 28 day strength. At later ages the general trend is for the CSF concrete to have a higher strength gain."

Results show "...that the silica fume concrete generally reacts favourably [sic] to curing in a hot environment whereas the normal portland cement concrete does not. That is, the CSF mixtures become less permeable when cured in a hot climate, and normal portland cement mixtures become more permeable."

The article reports the following conclusions:

"There appears to be very little published data on the influence of curing on the permeability/absorption of silica fume concretes. This research has not only confirmed the superiority of silica fume concretes over equivalent normal portland cement mixtures, but has also demonstrated the impact of the nature and length of the initial curing on surface permeability, and hence potential durability. In particular, silica fume concretes respond favourably [sic] to hot climates provided at least two days moist curing is provided.

Four days moist curing reduces the permeability of a CSF concrete by a factor of 3 to 4 over that achieved with just a one day cure; this factor can be even greater in a hot climate. In equivalent normal portland cement concretes the reduction is only around 50%, and the resulting permeability is generally higher than that of the CSF mixture. A silica fume concrete's permeability reduces more rapidly during the first two months, presumably due to the pore refining effect in this period.

The beneficial effect of hot weather curing on condensed silica fume concretes is clearly reflected in the permeability and absorption measurements. The greatest difference between temperate and hot cured values was obtained with the lowest strength mixture.... Whilst there was a clear trend of permeability/absorption decreasing with strength for a particular concrete mixture tested at different ages, the results for different mixtures generally lie on different curves. Strength alone is not a reliable indicator of the permeability/absorption characteristics of CSF concretes."

4.44 **Parrott, P. J., DESIGN FOR AVOIDING DAMAGE DUE TO CARBONATION-INDUCED CORROSION, pp. 283-298.**

"Published field and laboratory data was used to formulate and validate a design method for avoiding damage due to carbonation-induced corrosion of reinforcement. It accounted for an initiation period, during which a carbonation front penetrates the cover concrete and a propagation period, during which the reinforcement corroded and produced visible cracking of the concrete. The initiation period was dependent upon the depth of cover, the permeability of cover concrete and the quantity of cement hydrates that buffer the carbonation reaction. The rates of carbonation and corrosion were dependent upon the relative humidity within the cover concrete. The main factors influencing the required concrete performance for a given exposure condition were the depth of cover and the notional service life; the effects of curing and cement type were less significant."

4.45 **Cao, H. T., Bucea, L., Wortley, B., and Sirivivatnanon, V., CORROSION BEHAVIORS OF STEEL EMBEDDED IN FLY ASH BLENDED CEMENTS, pp. 215-227.**

"In this paper corrosion characteristics of steel embedded in hardened cement pastes and mortars were investigated by using data obtained from potentiodynamic anodic polarization and polarization resistance techniques."

Results indicate that "...with prolonged curing, steel embedded in fly ash blended cement pastes was found to have a higher degree of passivation with greater stability than that embedded in plain cement paste. Chloride binding capacity of 40 percent fly ash blended cement paste as indicated by the measured corrosion rate of steel was found to be very effective after 3 days of curing."

The authors "...found that the use of fly ash did not lead to any interference on the passivation of steel even at high dosage of 60 percent and prolonged curing of 2 years."

4.46 **Luther, M. D., Mikols, W. J., DeMaio, A. J., and Whitlinger, J. E., SCALING RESISTANCE OF GROUND GRANULATED BLAST FURNACE (GGBF) SLAG CONCRETES, pp. 47-64.**

"This laboratory and field investigation studied the de-icer scaling resistance of ground granulated blast-furnace (GGBF) slag concretes. The laboratory part of the investigation used the ASTM C 672 test with up to four different curing routines: air, curing compound, the standard procedure, and wet. The field part evaluated three curing routines: air, curing compound, and intermittent wet cure. It also evaluated two different finishing tools, and the effect of a linseed oil-kerosene sealer applied at 90 days."

"In the laboratory, the different curing routines did not clearly affect scaling. Use of curing compound on the concretes in the field, which were all exposed to chlorides, essentially eliminated scaling. Also, application of a sealer to mature dry concrete greatly reduced or eliminated scaling. Continuous air curing (bad practice) was associated with increased scaling in all concretes."

The following conclusions were reported:

"In the laboratory, the various curing routines studied did not clearly affect scaling. In the field and regardless of GGBF slag dose, continuously air-cured (bad practice) concretes scaled far more than intermittently wetted concrete. Curing compound use usually eliminated scaling altogether; and, the application of a sealer after the concrete matured and dried also greatly reduced the incidence of scaling."

4.47 **Marchand, J., Sellevold, E. J., and Pigeon, M., THE DEICER SALT SCALING DETERIORATION OF CONCRETE—AN OVERVIEW, pp. 1-46.**

"Curing, primarily because of its influence on the capillary porosity of the hardened paste, is obviously very important as regards durability.... This...is particularly true for deicer salt scaling resistance, since curing mostly affects the surface layers of concrete. Furthermore, in many cases, if curing procedures are delayed, plastic shrinkage cracking can occur, and surface durability can thus be significantly reduced.

Although the reasons for this are not always well understood, the type of curing can have a very significant influence on the scaling resistance. Many authors have reported in recent years that concretes cured with a membrane forming curing compound have a better scaling resistance than similar water cured concretes. This has been found to be true in laboratory..., as well as field experiments...."

"The deicer salt scaling resistance of concrete can be significantly improve[d] by air entrainment, appropriate curing and good concreting practices. Unfortunately, even when all these conditions are met concrete surfaces can nevertheless suffer from scaling."

NOTE: Items numbered 4.48 through 4.54 below are from the **INTERNATIONAL WORKSHOP ON HIGH PERFORMANCE CONCRETE,** NOVEMBER, 1994, ACI SP-159, American Concrete Institute

4.48 **Ahmad, Shuaib H., Russell, Henry G., and Zia, Paul, SUMMARY OF THE WORKSHOP, pp. 1-7.**

There is an increasing interest in HPC around the world. HPC is being used in a variety of applications.

The development of flowable (self-compacting) concrete in Japan appears to be advancing rapidly.

Emphasis is being placed on the issue of durability as well as high strength.

"In many applications of HPC, especially below 70 MPa (10,150 psi), silica fume is not needed for strength but is used to enhance workability. The experience with HPC in Thailand indicated that workability was the first concern, followed by high strengths. Today both aspects are combined in the production of HPC in Thailand."

Quality assurance is important to concrete construction, especially for HPC.

"Curing and early age cracking are important issues.... Early age cracking due to plastic shrinkage may be a problem in flat surfaces and has to be avoided by immediate curing. However, curing is perhaps the process that is least understood, widely neglected or improperly handled at the job site."

"Durability remains a major consideration in many HPC applications worldwide."

"Limits on concrete strength are imposed by different national codes. In France, concretes with compressive strengths of up to 60 MPa (8,700 psi) are acceptable in all reinforced and prestressed concrete structures. From 60 to 80 MPa (8,700 to 11,600 psi), permission is granted on a case-by-case basis. Beyond 80 MPa (11,600 psi), a special investigation of the particular application is required. In Germany, current use is up to 55 MPa (8,000 psi), with anything above that limit requiring a special study. In Norway, the current acceptable limit is 100 MPa (14,500 psi). It was also revealed that in Europe, standards will soon be established with a compressive strength limit of 105 MPa (15,200 psi). In the USA, no concrete strength limit has been established by the building code except that in the design for shear and development length the concrete strength may not exceed 70 MPa (10,150 psi). The U. S. code standards are often followed by other non-European countries.

Currently, the use of high performance concrete, with strength between 35 and 60 MPa (5,000 and 8,700 psi), is about 5% to 10% of the total amount of concrete used in France, and that seems to be the case in the rest of Europe as well."

"All new nuclear power plants in France will use high performance concrete. An application of particular interest in Germany is the use of HPC in containers for toxic materials or in impervious barriers to organic hazardous waste.

In North America, the traditional application of HPC has been in columns of high-rise buildings, but more recently the focus has shifted to the use of higher strength concretes for bridge girders. [...] Increased emphasis is being placed on applications where durability is important."

"The current perception by the user-owner is that high performance concrete is a concrete with high strength and high cost."

Issues with HPC that must be addressed include:

- How can the effect of curing be quantified?
- How can one measure and quantify durability for all exposure conditions?
- There is a lack of an appropriate methodology to evaluate service life of a concrete structure.

Research needs include:

- "Conduct research on improved methods to quantify durability."
- "Monitor and evaluate performance records of existing high performance concrete applications."

4.49 **Reinhardt, Hans W., REPORT ON SESSION I—HPC IN THE PACIFIC RIM, pp. 9-12.**

"Workability was a first challenge for HPC in Thailand, followed by high strength. Now, both aspects are combined to make up modern HPC." Reports from Taiwan reveal "...the habit of adding water to fresh concrete by untrained workers still persists." Japan continues to focus on the development of a self-compacting HPC.

Heat of hydration, curing, and early age cracking are important aspects of HPC in the first four days of age. "To produce a curing insensitive concrete which needs only 24 hours curing would be a great achievement.... Early age cracking due to plastic shrinkage may be a problem at horizontal surfaces and has to be avoided by immediate curing."

"Ductility is seen as a requirement for safe structures. [...] The design of a ductile structure made of brittle materials is a challenge for further research."

4.50 **Naaman, Antoine E., REPORT ON SESSION II—HPC IN EUROPE, pp. 13-16.**

Some have suggested service lives of more than one hundred years are possible with HPC under normal conditions.

"The lack of durability of HPC can be overcome by addition of fibers."

"Since the world population may double over the next fifty years, the demand for improved building materials such as HPC is likely to be phenomenal; this justifies large investments in research in HPC."

"There is a true need to further document and quantify the durability of HPC, especially since durability is suggested as an essential part of the definition."

4.51 **Swamy, R. Narayan, REPORT ON SESSION III—HPC IN NORTH AMERICA, pp. 17-22.**

"In this vast program for researching and implementing the use of high performance concrete, a coordinated research program relating microstructure with engineering properties and structural performance is critical if we are to provide the technical basis and tools for optimization needed to facilitate the design of structures utilizing HPC and other new cementitious systems."

"Although there is currently some controversy concerning the need for air-entrainment for freeze-thaw durability of HPC, air entrainment has other benefits, and clearly enhances the rheological properties of concrete even if there is a strength loss of 4-5% for each 1% air content."

Recent data has indicated no in-place strength loss occurred in actual structures built with high strength concrete after 18 years' service life, whether due to heat of hydration or other material degradation.

"The issue of durability is still very much in debate, and whether we can quantify it as well as characterize and quantify the local environment—the microclimate—which ultimately decides the serviceability of structures, in a way that can be understood and adopted by practicing engineers, is still uncertain."

We need to know and understand more about curing of HPC. "How effective is curing—in other words, how do we enable concrete placed in an aggressive microclimate to develop its strength and impermeability satisfactorily, and maintain these properties with time? Plastic shrinkage cracking has been a source of deterioration in many constructions, and what is the best approach—mesh or fibers—to contain their damaging effects?"

"Engineers can learn a great deal from information obtained from structures in service and exposed to aggressive environments, and one of our top priorities in research should be to monitor the performance of such structures, built with HPC, over a sufficiently long period of time to enable us to draw valid conclusions."

4.52 **Ryan, W. G. and Potter, R. J., RESEARCH NEEDS FOR HPC—AN AUSTRALIAN PERSPECTIVE, pp. 103-116.**

"The purpose of this paper is to evaluate research needs for High Performance Concrete (HPC) given the anticipated markets for concrete in Australia over the next ten years." The authors state that "...because of the limited funds available for concrete research, research around the world needs to be coordinated to avoid duplication of effort."

"High-Performance Concrete may be defined as concrete that meets multiple performance criteria that are significantly more stringent than those required for normal structural concrete."

There is a desire for buildings to have a working life longer than the base of 40-60 years mentioned in the current Australian codes. New specifications by The Roads and Traffic Authority of New South Wales emphasize durability as having prime importance. HPC will be expected to provide the required durability if it is to receive wide acceptance.

Curing still is an area in which corners are cut on the job site. "While supervisors may acknowledge its value, the project schedule does not permit three days moist curing let alone seven or longer. While the effects of this in a temperate climate may be bad, in the dry warm climate of Australia the problems are exacerbated."

The authors believe "...we should be investigating binder systems and concretes which do not require any further curing after 24 hours. Such concretes would be a boon circumventing the world-wide problem of lack of curing, which we cannot seem to solve."

The top priority research need for HPC in Australia concerns curing, as follows:

- "To investigate the effect of accelerated curing regimes on the long-term strength and durability of the new and to be developed binders.
- To develop a binder which does not require curing beyond 24 hours to achieve its desired performance."

4.53 **Sellevold, Erik J., HIGH-PERFORMANCE CONCRETE: EARLY AGE CRACKING, PORE STRUCTURE, AND DURABILITY, pp. 193-208.**

"Practical use of high strength concrete in Norway has shown that it is susceptible to cracking at early ages, and that it normally is subjected to high curing temperatures due to high cement contents." This paper looks at "...the consequences of elevated curing temperatures on pore structure characteristics, permeability to chloride ions and frost resistance of high performance concrete."

It is clear "...that increased curing temperatures leads to increased ice formation at temperatures down to -20 °C (-4 °F) , demonstrating increased coarseness and continuity of the pore structure." Results from these studies for HPC verify that increased curing temperature causes a coarser and more continuous pore structure. The effect of increased curing temperature is to increase the transport rate of chloride migration. Concretes showed increased scaling with increased curing temperature. Laboratory results concerning frost resistance were inconclusive which underscores the need to conduct on site studies on real structures under various severe exposure conditions.

4.54 **Elfgren, L., Fagerlund, G., and Skarendahl, A., SWEDISH R & D PROGRAM ON HIGH-PERFORMANCE CONCRETE, pp. 247-261.**

"A consortium of six companies and two governmental research funding organisations [sic] are carrying out a six-year research and development program on high performance concrete in Sweden."

"The program is divided into 17 different subprojects that are grouped under the headings of materials, production technique, and structures." Curing is one of the areas under production technique.

"The most important parameter in improving concrete performance is the water/binder ratio, i.e., the denseness of the material. Very often high performance concrete thus is synonymous with the use of a low water/binder ratio, and the ability of rational casting and compaction."

"The aim of the curing project is to study how the conditions of curing affect the final properties of high performance concrete. Heat curing, use of warm fresh concrete as well as the degree of moisture during curing are considered. Special attention is given the question of plastic shrinkage following indications of higher sensitivity to plastic shrinkage cracking for high performance concrete mixes. The project is aiming at increasing the understanding of measured effects from various curing methods as well as to develop recommendations on the choice of curing procedures.

A part of the project work has concentrated on studying changes in the microstructure that follows various heat treatments. The effects on mechanical as well as physical properties have been studied on laboratory and in situ concrete being subjected to heat curing. Studies on plastic shrinkage require knowledge about fracture mechanic properties during the very early age. Models for the plastic shrinkage cracking process are developed and tested in laboratory scale and in in-situ applications."

5. LITERATURE FROM 1995 TO 1996

5.1 **Cabrera, J. G., Claisse, P. A., and Hunt, D. N., A STATISTICAL ANALYSIS OF THE FACTORS WHICH CONTRIBUTE TO THE CORROSION OF STEEL IN PORTLAND CEMENT AND SILICA FUME CONCRETE, Construction and Building Materials, Vol. 9, No. 2, April 1995, pp. 105-113.**

"The corrosion of embedded reinforcement...[was] measured in two series of concrete samples made with and without condensed silica fume (CSF) as a partial replacement for the cement. Three different curing regimes were used and samples were tested at three different ages. [...] The statistical analysis showed that while the corrosion rate was affected by the water/cement ratio and the curing for all samples the use of CSF significantly increased the sensitivity to poor curing."

"In this paper a statistical analysis of a set of experimental results on OPC [ordinary portland cement] and CSF mixes is presented. The results are from laboratory measurements of corrosion by linear polarization resistance measurement and of various transport properties of the mixes." One objective of the analysis was: "To show the importance of the different aspects of the materials and methods used in construction (e.g., the water/cement ratio and the curing conditions) on the corrosion rates."

The three curing conditions were intended "...to cover the range of curing environments which would be encountered on a reasonably well managed construction site." They are as follows:

1. 20 °C (68 °F) and 99% RH until test age
2. Treated with aluminum pigmented curing agent and kept at 20 °C (68 °F) for 7 days and then in water at 5 °C (41 °F)
3. In water at 5 °C (41 °F) until test age

Specimens were tested at 3, 28 and 90 days. Four different concrete mixtures were used. "All combinations of the four mixes, three curing conditions and three test ages were used for the tests giving a total of 36 'sample conditions' which reflect a wide range of possible conditions for site concrete when first exposed to an aggressive environment."

Changes in w/c ratio made the concretes significantly more sensitive to curing. With respect to corrosion resistance, the results show: "For curing conditions 1 and 2 the CSF mixes are significantly better than the OPC mixes, and the low w/c ratio mixes are significantly better than the high w/c ratio mixes. For curing condition 3 {the 5 °C (41 °F) condition} there are no significant differences between the mixes except for the low w/c ratio CSF mix. The similarity between the corrosion rates for curing condition 3 could have been caused by the general inhibition of the hydration process preventing the potentially 'better' mixes from developing corrosion resistance. The superior performance of the low w/c ratio CSF mix may simply have been caused by self desiccation leaving the steel in a dry environment. It has been shown that at 5 °C (41 °F) (curing condition 3) the pozzolanic reaction in the CSF mixes will not have started even at 90 days so it will not have improved the transport properties."

Test results confirmed "...that changes in mix type from OPC to CSF make the initial corrosion current significantly more sensitive to changes in curing."

One of the important conclusions from this paper is that "...the use of CSF in concrete makes it significantly more sensitive to changes in curing."

5.2 **Khan, Mohammad Shamim and Ayers, Michael E., MINIMUM LENGTH OF CURING OF SILICA FUME CONCRETE, Journal of Materials in Civil Engineering, Volume 7, No. 2, May 1995, pp. 134-139.**

The authors "...identified the curing requirement as one of the aspects of silica fume (SF) concrete that needs to be further explored to use SF concrete to its full potential. There are few studies in the available literature that specifically deal with the curing requirement of SF concrete. However, several studies concerning SF concrete have included curing as one of the variables, and thereby provided limited data on the curing sensitivity of SF concretes."

The main objective of the study presented in this paper "...is to determine the minimum length of moist curing for specific SF concrete mixtures, and to compare these results with those of plain PC concrete and fly ash (FA) concrete mixes."

"The materials used in the present study included ASTM Type I portland cement, Class F fly ash, SF, limestone coarse aggregate, a high-range water-reducing admixture (HRWA), and an air-entraining admixture (AEA). A dry uncompacted SF from silicon production was used. The water absorption of coarse aggregate was 0.68% and 0.45%, respectively.

Four SF concrete mixes, one FA concrete mix, and one plain PC concrete mix were investigated."

"A common feature of all the mixes was a total cementitious material content of 450 kg/m^3 (758 lb/yd^3), a water-to-cementitious-material ratio of 0.38, and a coarse-to-fine aggregate ratio of 1.5."

"The relatively low curing requirement of SF concrete, as suggested by the data in...[this] study, can be explained by the mechanism of strength development in SF concrete. According to Roy (1989), the hydration of C_3S (Ca_3SiO_5), the cement compound primarily responsible for strength development at early stages, is accelerated in the presence of SF particles."

"The high early strength development in SF concrete may also be attributed to an early pozzolanic reaction."

Some conclusions from this paper are:

"The minimum length of curing for specific SF concrete mixes, as determined by the equations developed in this study at laboratory temperature, is approximately 3 days. Compared to this, the minimum length of curing for a typical plain Type I PC concrete mix is 3.75 days, and that for a 15% Class F fly ash concrete mix 6.5 days. Note that this conclusion is based on a specific set of concrete mixes and it should be experimentally verified whether these curing periods are applicable to other concrete mix formulations as well. Although, the results obtained in this study indicate that the minimum length of moist curing required for SF concrete is less than that for plain PC concrete, it is conservatively recommended that SF concretes be cured according to the requirements of the PC (ACI 308-81(86) guidelines) with which they are blended. Before fully establishing the curing requirements, involving several other important performance measures, it would be unwise to adopt a shorter curing duration. The results in...[this paper] relate to strength, and it is not clear how they would relate to other measures of performance like permeability and electrical conductivity. [...] The length of curing should be optimized in terms of several other properties, including tensile and flexural strength, permeability and the resistance to chloride, and sulfate penetration. [...] Note that ACI 308-81(86) recommends the determination of the minimum length of moist curing on the basis of strength only."

5.3 **Aitcin, Pierre-Claude, CONCRETE THE MOST WIDELY USED CONSTRUCTION MATERIAL, Proceedings of the Adam Neville Symposium on Concrete Technology, Las Vegas, NV, June 1995, pp. 257-266.**

The author states that "...concrete is too often abused during placing and curing so that an adequate concrete is transformed into a low performance one."

Concrete "...is not very expensive and when properly designed, mixed, transported, placed, and cured, it is a durable material in most of the usual environmental conditions."

Concrete must be adequately cured after casting.

"At the end of the production cycle of concrete, that is, during its placing and curing, concrete performance is usually in the hands of poorly educated manpower. [...] As a consequence a well designed concrete structure, for which a well designed mix has been delivered, can perform poorly following bad placing and curing practice."

5.4 **Dolch, W. L., SORPTIVITY AND ITS USES, Proceedings of the Adam Neville Symposium on Concrete Technology, Las Vegas, NV, June 1995, pp. 147-160.**

"Sorptivity is a quantitative measure of the speed of absorption of a liquid by a porous solid."

ASTM uses sorptivity to determine the effectiveness of curing compounds (ASTM Method C 1151).

The author says that "...for concrete, the surface is often the region of greatest interest, because of its strong influence on the durability of the concrete."

It seems logical that "...sorptivity should serve as a measure of quality of concrete, since larger porosities and pore sizes are associated with higher w/c [ratios] and poorer quality."

"Sorptivity has been used as an index of the quality of the concrete surface as affected by the type of curing...." Researchers have "...found the expected inverse relationship between sorptivity and the duration of curing or the humidity of the environment of the concrete. Ho [1984] proposed explicitly that sorptivity be considered an inverse measure of the quality of concrete."

The article concludes "...that the sorptivity method is not yet an accurate way to determine the pore parameters of cement paste or concrete."

5.5 **Ozaka, Yoshio, REALIZATION OF HIGH STRENGTH CONCRETE IN JAPAN, Proceedings of the Adam Neville Symposium on Concrete Technology, Las Vegas, NV, June 1995, pp. 30-58.**

Use of high-strength concrete (HSC) on No. 2 Ayaragi-gawa Bridge: "Moist curing was performed by completely covering each girder with sheets to minimize the temperature difference between the interior and surfaces of the girder."

Inahava Bridge use of HSC: "No special consideration was given to curing which was done in the same manner as for ordinary concrete."

A small bridge of silica-fume concrete: "Girders of silica-fume concrete were cured by steam and compressive strength of the concrete was estimated to increase rapidly to 90 N/mm^2 (13,000 psi) in a day and to exceed 108 N/mm^2 (15,700 psi) in 28 days."

5.6 **Chirgwin, Gordon J. and Ho, David WS, THE RTA APPROACH AND THE USE OF WATER SORPTIVITY FOR COMPARING THE DURABILITY QUALITY OF CONCRETE, Proceedings of the Adam Neville Symposium on Concrete Technology, Las Vegas, NV, JUNE 1995, pp. 85-101.**

"New materials and methods for concrete are being proposed, but many of these depend upon research based on water curing of the concrete. Owners of major infrastructure are experiencing premature deterioration of concrete structures. It is believed that this early deterioration is, in part, caused by inadequate mix design and curing methods.

The Roads and Traffic Authority [RTA] of New South Wales, Australia, has made use of water sorptivity to ensure that the concrete is designed to take account of the real curing conditions. The method allows comparison of the differences in curing between 'standard moist curing' and real curing, and the effects upon the concrete quality."

One of the principal causes of large scale cracking is inadequate finishing and curing.

"Early Quality Assurance Contracts specified curing in a prescriptive manner, and not related to the concrete design. Also, the specifications assumed that all forms of curing were equal, and took no account of either practical construction limitations or changes in cements.

The tendency is for curing to be regarded as too difficult to perform, and therefore, to be ignored."

"Assuming that suitable materials have been selected, low permeability is obtained by suitable mix design, good compaction, and appropriate curing."

The authors state "...that for low permeability in the cover concrete, we require fairly high cement contents and low water-cement ratios. In addition, we need appropriate curing (i.e., additional water) to allow the cement to keep hydrating after set has occurred."

"Ho and Powers [1992 and 1959] demonstrated that the water-cement ratio had a significant bearing on the time for curing to achieve a given impermeability.

For a water-cement ratio of about 0.45, Ho [1992] has shown that it takes between 7 and 21 days of water curing to achieve effective impermeability using TYPE A Cement, and that the early curing is most critical."

This article says "...the need for curing and the period of curing required depend upon three factors:

- the durability required from the concrete taking into account the exposure classification;

- the cement content and type;
- the water-cement ratio of the mix.

Also, concrete mixes fall into three classes:

- where the water-cement ratio is so high that no amount of curing will produce impermeable concrete (above about 0.65);
- where the water-cement ratio is such that additional water curing is required to achieve impermeability (about 0.35 to 0.50);
- where the water-cement ratio is so low that in practice, no further water can penetrate the concrete, despite only very limited curing (below about 0.35).

Ho and Powers also showed that, for a given proportioning of the dry constituents, reducing the water-cement ratio, reduces the water curing required to achieve a given impermeability.

Ho also demonstrates that the various methods which are commonly used for curing are not equivalent. In particular, covering with plastic gives demonstrably more permeable concrete than water curing when the same mix is used...."

"So, for a given exposure classification, we can achieve the required durability by extended curing, or increased cement content and reduced water/cement ratio with reduced curing."

"Commercial pressures on contractors tend to require the shortest possible curing time."

RTA plans to substantially strengthen the definition of curing within its specifications.

"Four curing regimes are defined:

- **Standard moist curing** - in accordance with AS 1012 for concrete test samples;

- **Wet curing** under reasonable ambient temperature conditions - which requires water at the surface of the concrete;

- **Sealed curing** under reasonable ambient temperature conditions - requiring the concrete surfaces to be sealed against the loss of water;
  and

- **Heat accelerated curing** with forms remaining in place - including 'steam' curing."

"The contractor is free to choose any curing regime, provided that the tests proposed demonstrate the performance of the mix when cured in accordance with the contractor's design is satisfactory."

"At this time, the only accepted curing for Silica Fume concretes in aggressive conditions is 24 to 48 hr sealed in forms plus 3 to 6 days water curing. The use of sealed curing has not been validated for long term performance, except for scaling resistance."

Concerning the finishing of unformed surfaces:

"The deck finishing and curing requirements now also include a limit on crack width measured at 7 days after curing."

RTA concludes one of the reasons for failures in performance of concretes in marine and near coastal environments has been inadequate curing.

5.7 **Hilsdorf, Hubert K., CRITERIA FOR THE DURATION OF CURING, Proceedings of the Adam Neville Symposium on Concrete Technology, Las Vegas, NV, June 1995, pp. 129-146.**

"In this paper the effects of curing on some concrete properties are summarized and the parameters which should be taken into account when setting up curing requirements are outlined."

"It is generally accepted that concrete has to be sufficiently cured, i.e., protected from early moisture loss and unfavorable temperatures during its early state of hydration in order to assure sufficient strength and durability properties of the hardened concrete at a later stage. In many practical instances curing of concrete is neglected, resulting in concrete structures with inadequate properties." Concerning curing, "...Adam Neville states: 'The necessity for curing arises from the fact that hydration of cement can take place only in water-filled capillaries. This is why a loss of water by evaporation from the capillaries must be prevented. Furthermore, water loss internally by self-desiccation has to be replaced by water from outside, i.e., ingress of water into the concrete must be made possible.'

The required duration of curing is a controversial matter." The author states that "...the required duration of curing will depend on the parameters controlling the rate of drying..., and on the question whether the average strength of a section or the properties of the surface layers are decisive for the performance of the structure."

"In the European prestandard ENV 206: 'Concrete-Performance Production and Compliance Criteria' minimum requirements for the duration of curing ranging from 1 to 15 days are given, depending on environmental conditions during curing, concrete temperature and rate of strength development of the concrete.... Similar values are recommended in the new CEB-FIP Model Code 1990...." Also, "...for the revision of ENV 206 presently under way, an attempt was made to define the criteria for the duration of curing more thoroughly."

Effects of Curing:
"The rate of *moisture loss* of young concrete exposed to drying decreases with increasing duration of curing." Test results show "...that the depth up to which the moisture content of the concrete is affected by drying decreases with increasing duration of curing. [...] The rate of moisture loss also depends on the rel. humidity of the surrounding air, wind velocity and concrete temperature....

It is generally accepted that the *compressive strength* of concrete increases with increasing duration of curing."

It has been shown "...that the effect of curing on compressive strength decreases with increasing specimen size and decreasing water-cement ratio. [...] The influence of curing on the *tensile strength* of concrete is similar to its effect on compressive strength, however, also the method of determining tensile strength is of significance, since different methods reveal different sensitivities of tensile strength to curing.

With increasing duration of curing, gas and water *permeability* of concrete decreases significantly." Laboratory tests have shown "...that the *rate of carbonation* of concrete decreases with increasing duration of curing."

"The *abrasion resistance* of concrete decreases significantly if the concrete is not cured sufficiently, because it is the surface layer of a concrete member which is responsible for abrasion resistance and which is affected most by insufficient curing...."

Parameters Influencing The Required Duration of Curing:
The author says "...the parameters which have to be taken into account when setting up curing requirements are summarized as follows:

Curing sensitivity of the concrete as influenced by its composition. The required duration of curing increases with decreasing rate of hydration of the concrete.... A decrease of water-cement ratio generally results in a reduction of the rate of hydration. However, concrete with a low water-cement ratio may reach a certain minimum strength or a certain impermeability after shorter curing periods than concretes with a higher water-cement ratio.

Concrete Temperature. Since the rate of hydration is strongly influenced by temperature, the duration of curing may be reduced for high concrete temperatures whereas it has to be increased for low temperatures. The effect of temperature may be taken into account on the basis of maturity considerations....

Ambient conditions during and after curing. A low relative humidity of the ambient air, sunshine and high winds accelerate drying of the unprotected concrete at an early stage of hydration.... Under such conditions curing should be prolonged, because after termination of curing the surface layers of the concrete dry out rapidly, and hydration will no longer continue. On the other hand, when concreting in a humid environment at moderate temperatures sufficient curing may be provided by the surrounding environment.

Exposure conditions of the structure in service. The more severe the exposure conditions the longer is the required duration of curing. This is of particular importance if the properties of the surface layers of a concrete member are of significance such as in the case of abrasion."

Curing Criteria:
With regard to "...estimating required durations of curing the following criteria have been considered:

- rate of carbonation
- permeability
- maturity or degree of hydration
- compressive strength

Carbonation
Carbonation of concrete may be a relevant criterion for the required duration of curing of reinforced concrete structures exposed to environmental conditions which may lead to corrosion of the reinforcing steel as soon as the cover concrete is carbonated so that it no longer provides sufficient corrosion protection." Field observations have shown "...that a significant rate of corrosion is to be expected only for exposure conditions which lead to the absorption of liquid water of the cover concrete by capillary suction. Such conditions may exist from concrete surfaces temporarily exposed to driving rain." It is stated that "...the required duration of curing may be estimated from the effect of curing on the rate of carbonation of concrete taking into account other significant parameters influencing carbonation. For such an estimate, also assumptions have to be made regarding the required life time of the structure and the thickness of the concrete cover."

Test data indicate that "...carbonation is a critical criterion for the duration of curing only for concrete made of blast furnace cements with a high slag content. It should be kept in mind, that lower values of the thickness of concrete cover [<25 mm (1 in.)] will yield substantially longer required durations of curing. [...] Also in regions when long periods of hot and dry weather are followed by a rainy and cooler season, carbonation induced corrosion may be of relevance even for a comparatively high thickness of the concrete cover, possibly requiring a prolonged duration of curing."

Permeability
"The required duration of curing may also be derived from the condition, that at the end of curing the concrete has reached a certain gas permeability. [...] The difficulty in setting up such a criterion is the proper choice of a value of gas permeability. There...[are few] data correlating durability properties with gas permeability. In addition, the permeability

coefficient of concrete strongly depends on the particular test method employed as well as on preconditioning the concrete specimens prior to the permeability measurement...."

"Permeability measurements of the cover concrete on site at the end of curing have been proposed as a measure to monitor effectiveness of curing...."

Maturity or Degree of Hydration

When using this as a criterion, "...curing has to be continued until the concrete has reached a certain maturity or degree of hydration."

Compressive Strength

"When using compressive strength of concrete at the end of curing as a criterion, two different approaches have been discussed:

- Concrete has to be cured until it reaches a certain minimum strength f_{cmc}, e.g., the strength of a reference concrete at the end of curing made of the same constituent materials with a water-cement ratio of 0.60 and cured for 7 days.
- Concrete has to be cured until a certain ratio of the compressive strength at the end of curing to the compressive strength at an age of 28 days $R = f_{cmc}/f_{cm28}$ is reached.

The advantage of the first approach is that—similar to the carbonation and the permeability criteria—a trade-off between curing time and water-cement ratio is possible: if the water-cement ratio is reduced also the duration of curing may be reduced. When applying the second concept, the strength and durability potentials of a particular concrete can be fully developed, and the duration of curing is independent of the water-cement ratio, however, it is a function of the rate of strength development of a particular concrete." It is noted that "...structural requirements should be taken into account. A logical criterion is the requirement, that the concrete in the structure has to be cured long enough so that at an age of 28 days it reaches the characteristic strength on which structural design is based." Also, "...the effect of curing on compressive strength is more pronounced for small cross-sections than it is for larger ones. Consequently, the required values of R should increase with decreasing size of the structural member." It is also pointed out that "...there is a lack of experimental data on the effect of curing on strength development of concrete made of modern cements, admixtures and additions." The author believes that "...it is likely that for moderate climatic conditions, a value of R = 0.70 is too conservative." Note: The value 0.70 refers to the ACI 308 recommendation that concrete should be cured until it attains 70% of its specified strength.

"When using the strength ratio approach and structural performance criteria, the observation that curing affects primarily the properties of the cover concrete of a concrete member may be of significance. However, ...a reduction of the compressive strength of the outer fibers of the compression zone of a reinforced concrete member due to insufficient curing has little influence on its flexural capacity, with the exception of very thin sections.

Another consideration is, that insufficient curing may have a negative effect on the bond between reinforcement and the cover concrete." In accordance with test results, "...the strength at a distance 25 mm (1 in.) from the surface is equal to that of the interior of the concrete section at an age of 28 days, if the concrete compressive strength at the end of curing is approx. 60 percent of the standard strength at an age of 28 days."

One of the concluding statements of the article is "...aside from problems in specifying experimental methods to conduct permeability measurements, limiting values of permeability to assure durability still have to be established. The same holds true for the criterion *maturity* at the end of curing."

"Compressive strength at the end of curing can be a suitable criterion to ensure both sufficient durability and structural performance." $R = 0.6$ has been proposed and justified.

5.8 **Parrott, L. J., INFLUENCE OF CEMENT TYPE AND CURING ON THE DRYING AND AIR PERMEABILITY OF COVER CONCRETE, Magazine of Concrete Research, 47, No. 171, June 1995, pp. 103-111.**

This article gives experimental results "...showing the influence of cement type and curing on the relative humidity, initial weight loss and air permeation in cover concrete that has been exposed to drying at 60% relative humidity for at least 18 months. Three curing periods (1, 3, and 28 days) and 17 cements were used, the cements differing mainly with respect to their contents of limestone or ground granulated blast furnace slag (ggbs). The concretes were all made with a water-cement ratio of 0.59 and the 28 day cube strengths ranged from 26 to 46 MPa (3,750 to 6,650 psi). The relative humidity at a mean depth of 25 mm (1 in.) below the exposed surface reduced to about 80% and 70% after 6 and 18 months of drying respectively. Cement type had little [effect] on the reduction of relative humidity with drying time and there was only a marginal retardation of drying rate with increased curing time. The initial four day weight loss, an indicator of moisture transport properties in cover concrete, reduced markedly as the curing period was increased. Increasing the ggbs content of the cement increased the initial four day weight loss with one day curing but reduced it with 28 day curing. The initial four day weight loss generally reduced as the strength at the end of the curing period was increased. The air permeability of cover concrete generally increased with drying time, even beyond 18 months; this effect was more pronounced with concretes that had lower permeabilities and appeared to be due to slow drying. On average the air permeability of cover concrete increased significantly with increasing drying time and decreasing curing period, but changes of greater magnitude could arise due to cement type. The compressive strength after curing, the initial four day weight loss and the 18 month air permeability were only broadly related. Concretes with 50% or more of ggbs in the cement tended to have a high air permeability for a given strength eight days after the end of curing or for a given initial four day weight loss."

"A reduction of relative humidity in the cover concrete due to early-age drying limits the degree of cement hydration, depending on cement reactivity, and prevents the potential performance of the concrete from being achieved.... The relative humidity in the cover concrete is also relevant to durability-related properties and to the rate of reinforcement corrosion."

5.9 **Sabir, B. B., HIGH-STRENGTH CONDENSED SILICA FUME CONCRETE, Magazine of Concrete Research, 47, No. 172, September 1995, pp. 219-226.**

"Tests to evaluate the compressive strength, tensile strength and static modulus of elasticity of concretes containing various levels of condensed silica fume (CSF) (microsilica) substitutions for portland cement were conducted at two water curing temperatures. [...] Although high-temperature curing (50 °C or 122 °F) accelerates the strength at early ages, the 91-day strength does not appear to be influenced by temperature. The curing temperature does not affect the observed relationships between the tensile strength, the modulus of elasticity and the compressive strength."

"The use of high-strength concrete can result in lower construction costs due to a significant reduction in the size of concrete members. This can be particularly advantageous for columns in terms of meeting long span requirements and reducing the quantities of reinforcing steel."

The strength gain pattern of CSF concrete has been studied by mainly concentrating on curing at 20 °C (68 °F). "Ronne [1990] studied the effect of curing conditions, with temperatures in the range 20-70 °C (68-158 °F), on the long-term compressive strength (up to two years) of concrete containing CSF and pulverized fuel ash (PFA). It was concluded that good initial curing conditions in the first three days gave an improvement in compressive strength over the samples dried immediately after demoulding [sic]."

It was observed "...that high-temperature curing accelerates the strength development of CSF concrete. Beyond 28 days, however, the strength gain is slower than for the reference concrete [without CSF].

The pattern of strength gain for CSF concrete is different to that of OPC [ordinary portland cement] concrete. Whereas it is generally accepted that the 7-day strength of normal concrete is of the order of 60%-70% of the 28-day strength, the results obtained... [with high-strength concrete] show a 7-day strength that is 86% of the 28-day strength for the specimens cured at 20 °C (68 °F) and 93% for those cured at 50 °C (122 °F). In the case of the CSF concrete, the average ratio of the 7-day to the 28-day strengths is 76% for the specimens cured at 20 °C (68 °F) and 97% for the specimens cured at 50 °C (122 °F)."

"In contrast to the strength development pattern at early ages, the 91-day strengths are higher for the specimens cured at 20 °C (68 °F) than for those cured at 50 °C (122 °F)."

Results indicate that "...it is clear that increased temperature can have a beneficial effect on the early strength development of CSF concrete."

Curing temperatures appear to "...have no significant influence on the observed relationship between the compressive and tensile strengths."

Likewise, "...the curing temperature does not have a significant effect on the relationship between the elasticity modulus and the compressive strength...." Compressive strengths greater than 90 MPa (13,000 psi) are associated with significant reductions in the values for modulus of elasticity.

5.10 **McCarter, W. J., Emerson, M., and Ezirim, H., PROPERTIES OF CONCRETE IN THE COVER ZONE: DEVELOPMENTS IN MONITORING TECHNIQUES, Magazine of Concrete Research, 47, No. 172, September 1995, pp. 243-251.**

"The work presented in this...[article] forms part of a wider research programme [sic] being undertaken on water and ionic movement within the cover region of structural concrete and the evaluation of the properties that, ultimately, determine durability. The developments in monitoring techniques employed in the testing programme... [focused] on the application of electrical methods." Results show "...that it is possible to determine such factors as rates and depths of water penetration, degree of saturation and porosity of the concrete cover, and the resistivity of the concrete at the level of the reinforcement."

"The performance of the surface zone has been acknowledged as a major factor governing the rate of degradation of concrete structures."

Water movement through the cover region involves unsaturated flow, and will involve capillary suction forces. "The ability of concrete to imbibe water by capillarity is taken as a starting point for grading the durability of concrete, and the term 'sorptivity' has been used in this respect.

The concept of using sorptivity as a durability indicator is comparatively new and there are, therefore, no standardized procedures or guidelines for the preparation of samples for testing, for experimental techniques, or for the interpretation and presentation of results."

5.11 **Wild, S., Sabir, B. B., and Khatib, J. M., FACTORS INFLUENCING STRENGTH DEVELOPMENT OF CONCRETE CONTAINING SILICA FUME, Cement and Concrete Research, Vol. 25, No. 7, October 1995, pp. 1567-1580.**

Results from this study "...establish that relative strength varies directly with CSF [condensed silica fume] content and that the strength enhancement at early curing periods, which is achieved by increase in curing temperature, is a result of increased reaction rate between $Ca(OH)_2$ and CSF."

The authors state that "...the major contribution to strength development of concrete within the first few days of curing is derived from alite hydration, with small contributions from belite hydration and hydration of the aluminate and ferrite phases. As curing progresses, belite hydration makes an increasing contribution to the strength development, and beyond 28 days, it is the principal contributor to strength gain, that from alite hydration becoming negligible."

Acceleration in hydration rate for the reference concrete (which did not contain any CSF) by increasing the curing temperature does not appear to enhance strength. In this study, the long term strengths for 50 °C (122 °F) cured concrete tend to be a little below those for 20 °C (68 °F) cured concrete. However, short term strengths of CSF concrete cured at the higher temperature of 50 °C (122 °F) were considerably in excess of those cured at 20 °C (68 °F).

Conclusions reported in this article are:

- "When curing at 20 °C (68 °F) the relative strength (ratio of strength to that of reference mix at same curing period and curing temperature) of CSF concrete increases rapidly within the first 21 days. Beyond 21 days, relative strength declines at low fume contents but continues to increase at high fume contents. This behaviour [sic] can be explained in relation to the time taken for an inhibiting layer of reaction product to form around CSF particles thus terminating the lime-fume reaction. The time taken for this to occur increases with increasing fume content.

- The increased hydration rate of the cement combined with the increased reaction rate of the CSF with lime when the curing temperature is raised to 50 ° (122 °F) results in a very marked increase in relative strength at very early ages. The near completion of these reactions within a few days leads to an overall decline in relative strength with curing time. However, a minimum develops in the relative strength-curing time curves with increased CSF content and it is suggested that this minimum results from the termination of cement hydration in the CSF concrete.

- At early ages, curing temperature has little effect on the strength of the control concrete, and at extended curing periods strengths of 50 °C (122 °F) cured concrete tend to be less than those of 20 °C (68 °F) cured concrete. It is suggested that this loss in strength is due to coarsening of calcium hydroxide crystals particularly at interfacial zones, which is an effect reported by a number of...[researchers]. Curing temperature does however have a very substantial effect on the strength of CSF concrete at early ages principally as a result of the increased rate of reaction of CSF with calcium hydroxide, although as might be expected, the ultimate strengths are very similar. Also there is a continuous increase in relative strength with CSF content at both curing temperatures and the magnitude of these increases is similar at both temperatures. This suggests that the CSF is performing the same function at both temperatures. It is suggested that this function is the formation of increasingly dense interfacial zones resulting from consumption of $Ca(OH)_2$ crystals by reaction with CSF."

5.12 **Mak, Swee Liang and Torii, Kazuyuki, STRENGTH DEVELOPMENT OF HIGH STRENGTH CONCRETES WITH AND WITHOUT SILICA FUME UNDER THE INFLUENCE OF HIGH HYDRATION TEMPERATURES, Cement and Concrete Research, Vol. 25, No. 8, December 1995, pp. 1791-1802.**

"A temperature match conditioning (TMC) system was developed and used to simulate the semi-adiabatic temperature development within medium sized high-strength concrete columns."

In this article, "...the strength development of two high-strength concretes with and without silica fume subject to the influence of high hydration temperatures is described."

"One of the primary objectives of this evaluation was to determine the influence of silica fume on concrete properties."

"The level of moist curing affected the strength of the PC [portland cement] concrete more than it did the SF [silica fume] concrete." Results indicated that "...the provision of full moist curing benefited the PC concrete to a larger extent when compared to the SF concrete."

Tests showed that "...the 1-year compressive strength of TMC cylinders was significantly lower than those cured at standard temperature."

"In the silica fume concrete undergoing TMC, ...hydration reactions stopped at a very early age due to self-desiccation."

In silica fume concrete, "...full hydration is neither achievable nor always a prerequisite for high strength development."

Conclusions from this article:

"High early age temperatures significantly accelerate the 7-day strength of a high-strength silica fume concrete with no significant increase in strength thereafter when compared to concrete cured at standard temperatures. By contrast, a high-strength PC concrete showed enhanced medium-term strength development due to high early age hydration temperatures.

The stagnated strength development of a silica fume high-strength concrete is consistent with the rapid stabilisation [sic] of non-evaporable water content as well as reduction in concrete humidity at very early ages due to self-desiccation.

The influence of high early age hydration temperatures on the strength development of high performance concretes differs markedly depending on the type of binder used. The combined effects of high hydration temperature and restricted moist curing led to a larger difference between TMC and standard cylinder strengths for a high-strength silica fume concrete when compared to a plain portland cement concrete of similar mix proportions."

5.13 **Vivekanandam, K. and Patnaikuni, I., MICROCRACKING IN HIGH PERFORMANCE CONCRETE DURING HYDRATION, Australian Civil Engineering Transactions, Vol. CE37, No. 4, December 1995, pp. 279-283.**

The summary of this paper states: "Condensed silica fume, a micro mineral, is found to have several advantages in high performance concrete production. The high strength enhancement is mainly due to micro filling and pozzolanic effects of the silica fume. This paper reports the Scanning Electron Microscopic studies on very high-strength concrete of up to 130 MPa (18,850 psi). Based on the study, it has been found that the silica fume addition either resists microcracking or deviates the path of microcracks. It has also been found that silica fume controls widening of the microcrack opening."

A silica fume content of 15% was used in this study. Cylinders were cured in a lime saturated water tank, and tested at ages of 3, 7, 14, 28, and 56 days.

Some of the major conclusions are:

- "Pozzolanic action is observed until 56 days in silica fume concrete.
- All the forms of silica fume particles have involvement in resisting formation and propagation of microcracks.
- High performance concrete with silica fume has lesser microcracks compared to normal strength concrete.
- A microcrack either stops or deviates when it encounters a silica fume particle."

5.14 STANDARD TEST METHOD FOR EVALUATING THE EFFECTIVENESS OF MATERIALS FOR CURING CONCRETE (C 1151), 1995 Annual Book of ASTM Standards, Section 4 Construction, Vol. 04.02, Concrete and Aggregates, pp. 609-612.

"This test method covers laboratory determination of the efficiency of liquid membrane-forming compounds and sheet materials for curing concrete."

A summary of the test method is described below:

"Three slabs of a standard mortar are molded and after 4 h, one is covered with the curing material to be tested, the second is tightly sealed with an impermeable lid, and the third is left uncovered. All three molds are stored in a test environment for 3 days. The test environment may be any set of conditions selected by the tester, provided only that a minimum rate of evaporation from a free-water surface of 0.4 $kg/m^2/h$ be maintained.

At the conclusion of the storage period, the slabs are demolded and three 25 mm (1 in.) diameter cores are cut at random from each of the slabs and stored under methanol for at least 24 h to stop the hydration of the cement and displace water. Using a diamond-blade saw and ethanol as the coolant, the top surface of each core is then sliced off, and from the remaining core, 1 cm (0.39 in) thick disks are cut from the top and the bottom, then placed in a vacuum desiccator for 24 h.

The absorptivity of each dried disk is determined by weighing it before and after a 60-s contact of its top surface with a water-saturated stack of filter paper. The difference in absorptivity of the top and bottom disks is a measure of the effectiveness of the curing."

5.15 Kern, Rudiger, Cervinka, Sarah, and Weber, Richard, EFFICIENCY OF CURING METHODS, Darmstadt Concrete, Vol. 10, 1995, pp. 117-122.

"Curing is generally recognized as one of the most important factors to influence the durability of concrete. It is necessary to ensure a sufficient hydration of concrete and... resistance against detrimental influences from outside. The efficiency of a curing method can be defined as the ability to keep the water in the concrete to guarantee high quantities of chemically bound water and thus to guarantee a high degree of hydration." This article reports on "...an experimental investigation...to determine quantitatively for different concrete compositions the amount of chemically bound water." These results "...will ultimately yield a detailed picture of the degree of effectiveness of the investigated curing methods."

In this study, "...different curing methods with and without addition of water were used to prevent the drying of concrete. The amount of evaporated water reduces the quantity of water available for the cement to react and is therefore related to the degree of hydration which determines the concrete durability. Hence, the efficiency of commonly used curing methods can be investigated by evaluation of the amount of chemically bound water."

Test results showed "...the significant influence of curing on the degree of hydration." This is evident "...from the strong rise of the amount of chemically bound water in the investigated non cured specimen cubes compared to cubes which were treated with wet coverings and vapour-proof [sic] sheets." It was concluded that efficiency of curing methods could be determined from the degree of hydration measurements.

5.16 **Schmelter, Ulrich, HYDRATION OF HIGH-STRENGTH CONCRETE FIRST RESULTS AND FUTURE PROJECTS, Darmstadt Concrete, Vol. 10, 1995, pp. 11-20.**

Specimens tested for compressive strength after 3 days showed that strength depends mainly on the w/c ratio. The influence of silica fume is very small. After 7 days, however, the influence of the silica fume on strength development increases. As the age increases, the influence of silica fume also increases. Maximum compressive strengths used in this study were about 120 MPa (17,400 psi). Results indicate that both the w/c ratio and the content of silica fume influence the relationship between the 28-day strength and the strength at an earlier age.

"With low water-cement ratios the hydration starts very fast. But after a certain time not much water is left to hydrate the cement, so the hydration declines very rapidly. With higher water-cement ratios the hydration takes a more steady course."

Future projects will focus on the influence of superplasticizers and temperature on the hydration and the durability of high-strength concrete.

5.17 **Weber, Silvia, and Reinhardt, Hans W., A BLEND OF AGGREGATES TO SUPPORT CURING OF CONCRETE, Proceedings, International Symposium on Structural Lightweight Aggregate Concrete, Ed. I. Holand, T. A. Hammer, and F. Fluge, Sandefjord, Norway, 1995, pp. 662-671.**

This article can be summarized as follows: "The replacement of a certain percentage of normal weight aggregates by lightweight aggregates creates a water storage inside the concrete which supports continuous wet curing. The results show that this idea can be successfully applied for obtaining high-strength concrete which is insensitive to curing conditions."

"Because it is impossible to supply exterior water to the interior of a real size structural member the idea was created to store water inside the concrete. This is possible by using lightweight aggregates with a high moisture content. On the other hand porous lightweight aggregates are less stiff and strong than normal weight aggregates and may thus adversely affect concrete strength. An optimization procedure was required between water supply and strength gain. The optimum would be a high-strength concrete which does not need curing." This article explains an optimization process developed by the authors.

The following curing conditions were investigated:

1. Six days under water, then in air at 20 °C (68 °), 65% RH
2. In air at 20 °C (68 °F), 65% RH
3. In air, temperature varying between 15 and 25 °C (59 and 77 °F), RH varying between 40 and 45%
4. Sealed in aluminum and polyamid foils

From the experimental work conducted, the best concrete mixture was one containing lightweight aggregates representing 25% of the total volume of aggregates. The w/c ratio was 0.33. The lightweight aggregates were submerged in water for 24 hours prior to being used. This concrete showed a higher compressive strength at 7 days than the concrete with normal weight aggregates for all the curing conditions. At an age of 28 days, the compressive strength of the lightweight aggregate concrete was higher for three of the four curing conditions used (Conditions 2, 3, and 4). At the age of 180 days, the compressive strength for the lightweight aggregate concrete was the same for each of the curing methods studied, and was at least as high as the standard compressive strength. So, the strength of the lightweight aggregate concrete compares very favorably with that of normal weight aggregate concrete, and is independent of the type of curing.

5.18 **Kjellsen, Knut O., HEAT CURING AND POST-HEAT CURING REGIMES OF HIGH-PERFORMANCE CONCRETE: INFLUENCE ON MICROSTRUCTURE AND C-S-H COMPOSITION, Cement and Concrete Research, Vol. 26, No. 2, February 1996, pp. 295-307.**

This article reports on "...a study on the effect of heat curing and post-heat curing conditions on the microstructure and C-S-H composition of a high-performance concrete. [...] Heat cured high-performance concrete showed a higher hollow shell porosity at later ages than a normally cured companion. Apparently the distribution of C-S-H throughout the cement paste matrix of the high-performance concretes was not significantly influenced by heat curing. However, the composition of the C-S-H phases was influenced by the curing regimes. The effect of heat curing on the microstructure appears to differ between high-performance and ordinary concretes."

"Concrete outside the laboratory cures at temperatures other than 20 °C (68 °F) and often under less than ideal moisture conditions. High curing temperatures may result from hot weather, accumulated heat of hydration or applied heat. Heat curing is used in the production of precast concrete products primarily in order to increase the early-age strength to allow for rapid production. It is often observed, however, that long-term properties are negatively influenced by elevated curing temperatures. Strength and other mechanical properties are often reduced and permeability increased.... It has been shown that curing at elevated temperatures may influence the microstructure considerably. [...] In pastes cured at high temperatures, relatively dense shells of reaction products formed around the hydrating cement grains, while the outer product phase remained relatively porous as relatively little reaction product formed in this phase."

The purpose of this study was "...to provide information about the microstructure and chemical composition of the C-S-H phases of heat cured high-performance concrete. Such information can be helpful in understanding the mechanisms of heat curing in high-performance concrete. [...] Curing cycles similar to those used in the production of precast products were simulated in the laboratory. The effects of heat treatment and post-heat curing conditions were studied. The post heat-curing conditions involved quite severe drying."

One high-performance concrete and one cement paste having a w/c ratio of 0.5 were studied in this project. The high-performance concrete had a w/(c + silica fume) ratio of 0.31. It contained a binder of 95% cement and 5% silica fume.

Some of the major conclusions reported are:

- "At later ages, the inner product phase of the 0.50 w/c ratio cement paste isothermally cured at 50 °C (122 °F) revealed a lower fine porosity than that of its outer product phase or the inner product phase of a companion specimen cured at 5 °C (41 °F). [...] The distribution of reaction products (C-S-H) throughout the cement paste matrix at later ages was much more uniform at relatively low curing temperatures."

- For the high-performance concrete, heat curing caused a higher hollow shell porosity at later ages than when cured at 20 °C (68 °F). "Less CH formed in previously formed hollow shells in the heat cured concrete, which is at least one reason for its higher hollow shell porosity. [...] The distribution of C-S-H in the bulk paste matrix was apparently not much influenced by heat curing. On the other hand, the composition of the C-S-H phases was influenced by the curing regimes."

5.19 **Goodspeed, Charles H., Vanikar, Suneel, and Cook, Raymond A., HIGH-PERFORMANCE CONCRETE DEFINED FOR HIGHWAY STRUCTURES, Concrete International, Vol. 18, No. 2, February 1996, pp. 62-67.**

"To establish a clear understanding of high performance concrete (HPC), the FHWA [Federal Highway Administration] is proposing to define HPC by using long-term performance criteria. The proposed definition consists of four durability and four strength parameters."

"A recent study conducted in the Chicago area evaluated the performance characteristics of commercially available concrete ranging in strength from 70 to 140 MPa (10,000 to 20,000 psi). This study demonstrated that a significant improvement in concrete durability resulted from an increase in strength. That HPC is not specified more frequently may be because engineers do not have confidence that higher strength concrete is more durable, that it can be reliably achieved in the field, that the higher strength can not always be used, or combinations thereof."

Both the Strategic Highway Research Program and the ACI definition of HPC refer to long-term performance parameters. "By restricting the definition to long-term performance parameters, concrete mixture designers may be more willing to incrementally modify mixture designs, change concrete curing procedures, and use admixtures and alternate hydraulic cements such as granulated ground blast furnace slag (ggbfs)."

"Mixture ingredients and proportions thereof, mixing sequence, curing conditions, and concrete permeability affect the ability of concrete in a saturated condition to resist deterioration when subjected to freezing and thawing."

"Curing history, water-cementitious [materials] ratio, air content, moisture content, characteristics of the freezing and thawing cycle, and salt concentration may affect concrete scaling resistance."

Eight parameters have been identified as sufficient to represent HPC long-term performance. They are: freeze/thaw durability, scaling resistance, abrasion resistance, chloride penetration, strength, elasticity, shrinkage, and creep. Grades of performance, numbered 1 through 4, are defined for each of the eight parameters. "Field condition severity was estimated for the full range of potential field conditions occurring in the United States...."

Standard laboratory tests, specimen preparation procedures, and grades of performance are suggested for each of the eight parameters used to define HPC. "Relationships between performance and severity of field conditions were estimated to assist designers in selecting the grade of HPC for a particular project."

5.20 **Tan, Kefeng and Gjorv, Odd E., PERFORMANCE OF CONCRETE UNDER DIFFERENT CURING CONDITIONS, Cement and Concrete Research, Vol. 26, No. 3, March 1996, pp. 355-361.**

This article deals with the effect of curing conditions on strength and permeability of concrete. "Test results showed that after 3 and 7 days moist curing only the concretes with w/c ratios equal to or less than 0.4 were accepted, while after 28 days of moist curing however, even the concrete with w/c ratio of 0.6 could be accepted. Silica fume has a significant effect on the resistance to water penetration."

"Proper curing is one of the essential means to get a durable concrete. It consists of the length of moist curing and the temperature of curing.

The hydration of cement can take place only when the vapour [sic] pressure in the capillaries is sufficiently high, about 0.8 [80%] of saturation pressure. Therefore early drying of concrete may stop the cement hydration before the pores are blocked by hydration products and thus a more continuous pore structure may be formed. The cover concrete is more sensitive to drying since it is prone to lose water. The formation of a continuous pore structure in cover concrete may provide an easy passage for the intrusion of aggressive species and therefore the deteriorating of the concrete structures. Early drying can also lead to more shrinkage and cracking and this would aggravate the deterioration process of concrete. Usually the concretes with lower w/c ratios are less sensitive to the curing.

It is well known that an elevated curing temperature will cause a low degree of hydration of cement at later ages and therefore a porous pore structure of cement paste and lower strength and higher permeability of concrete. However, not enough information is available for the curing conditions occurring in large scale concrete production, in which an elevated temperature could develop due to the release of the heat of cement hydration.

In this study, the permeability of concrete was tested based on the test methods of NS 3420 and ISO/DIS 7031, in which the maximum penetration depth of 25 mm (1 in.) was taken as a criterion for the acceptance/rejection of concretes. The objective of this study was to investigate which concrete at what curing conditions could be acceptable, and to provide some guidance for the concreting practices in aggressive environments." The variables considered included w/c ratio and silica fume.

As would be expected, "...the compressive strength under [the] standard curing condition...decreased as the w/c ratio increased. The incorporation of silica fume increased the compressive strength of concrete up to 30%."

Elevated curing temperature affected the compressive strength of high-strength lightweight concrete (HSLWC) "...to a much less significant level than that of normal strength concrete. This may be because the cement particles of closely packed in HSLWC and the hydration products from early hydration of cement are sufficient to fill the gaps between cement particles. Therefore the lower hydration rate at later ages caused by elevated curing temperature would not present any problem to HSLWC."

Silica fume concretes showed a much higher resistance to water penetration than those without silica fume.

Tests showed that "...no effect was found on the water penetration when concrete was cured at elevated temperature levels. However, the curing temperature affected the rate of chloride penetration significantly."

Major conclusions from this study are:

1. "The compressive strength of concrete decreases as the w/c ratio increases.

2. The incorporation of silica fume significantly increased the compressive strength up to 30%.

3. At the same age, concretes (with and without silica fume) with 3 and 7 days of moist curing have higher compressive strengths compared to those with 28 days of curing. This may be attributed to the removal of moisture from the interlayer of cement gel.

4. From the compressive strength point of view, the concrete with silica fume is less sensitive to early drying compared to that without.

5. The curing temperature significantly affected the strength of normal concrete, but not that of the high-strength concrete.

6. For 3 and 7 days of moist curing, only the concretes with w/c ratios equal to or less than 0.4 can be accepted based on the water penetration test, while for 28 days of moist curing, even the concrete with w/c ratio as high as 0.6 can be accepted.

7. Concrete with silica fume has a higher resistance to the water penetration compared to that without.

8. Elevated curing temperature doesn't affect the resistance to water penetration of concrete, but it does decrease the resistance to chloride penetration."

5.21 **Parrot, L. J., SOME EFFECTS OF CEMENT AND CURING UPON CARBONATION AND REINFORCEMENT CORROSION IN CONCRETE, Materials and Structures, Vol. 29, No. 187, April 1996, pp. 164-173.**

This article gives experimental data "...to illustrate the effects of cement type and curing upon the depth of carbonation and reinforcement corrosion in cover concrete after exposure for 18 months at 20 °C (68 °F) and 60% relative humidity. Three curing periods (1, 3, and 28-days) and 17 cements, with various proportions of granulated blast furnace slag or limestone, were used to make concretes, at 0.59 water/cement ratio, with 28 day strengths in the range 26 to 46 MPa (3,800 to 6,700 psi). The depth of carbonation after 18 months was 64% greater than after 6 months and was affected more by cement type than by curing."

The data showed that "...curing had little effect upon the rate of corrosion but higher rates were observed when the cement contained granulated blast furnace slag."

"The concretes used were all made with a free water/cement ratio of 0.59 and a cement content of 320 kg/m^3 (20 lb/ft^3)."

Results showed "...depths of carbonation for 1 and 28 days' curing are about 124% and 73% of those for 3 day curing, respectively."

The author concluded that "...cement type and curing seem to influence carbonation mainly through their effects upon the pore structure and gas transport properties of cover concrete; the more reactive the cement and the longer the period of curing, the lower the permeability and the rate of carbonation."

5.22 **Miyazawa, S. and Monteiro, P. J. M., VOLUME CHANGE OF HIGH-STRENGTH CONCRETE IN MOIST CONDITIONS, Cement and Concrete Research, Vol. 26, No. 4, April 1996, pp. 567-572.**

"This paper reports results of length change over time of high-strength cement paste, mortar, and concrete in moist conditions. The effect of specimen size, water-to-cement ratio and type and size of aggregate on the water absorption and length change were also investigated. Water permeation depth was calculated based on the increase in mass of the specimen and on the theoretical chemical shrinkage."

"Autogenous volume change is defined as the macroscopic volume reduction that is not caused by evaporation or temperature change, but by self-desiccation due to chemical reactions. Until recently it was assumed that autogenous volume change of ordinary concrete is so small as to be ignored in the estimation and control of cracking.... Recent research, however, has demonstrated that autogenous shrinkage of high-strength concrete can be quite large..., and it should be considered in the control of cracking...."

"The permeability of concrete depends not only on the permeability of the cement paste and of the aggregates, but also on the characteristics of the transition zone between the aggregate and the cement paste." The permeability of the transition zone increases with the size of the aggregate.

Cement paste beams were cast with these dimensions: 13 x 25 x 279 mm (0.5 x 1.0 x 11 in.); 25 x 25 x 279 mm (1.0 x 1.0 x 11 in.); 38 x 38 x 279 mm (1.5 x 1.5 x 11 in.) ; 76 x 76 x 279 mm (3 x 3 x 11 in.) ; and 102 x 102 x 279 mm (4.0 x 4.0 x 11 in.). Mortar and concrete beams had these dimensions: 102 x 102 x 279 mm (4.0 x 4.0 x 11 in.). Surfaces were sealed to provide for two-dimensional moisture flow into the specimen.

Conclusions from this experimental research were "...that increase in volume occurred in small cement paste specimens in moist conditions while larger specimens decreased in volume during the first two weeks of testing [storage in a fog room]. Because the curing water can only permeate the surface layer of the specimen, the inside of the specimen is subjected to self-desiccation, thus leading to a size effect in the prediction of length change.

High-strength concrete samples in moist conditions had a higher decrease in volume than the mortar samples containing the same aggregate volume fraction. This difference is attributed to the higher porosity in the transition zone between the aggregate and cement paste. The self-stress caused by restrained autogenous volume change can be large, and should be taken into account when designing high-strength concrete structures."

5.23 **Pinto, Roberto C. A. and Hover, K. C., FURTHER STUDIES ON THE UTILIZATION OF MATURITY FUNCTIONS TO A HIGH STRENGTH CONCRETE MIXTURE, 4th International Symposium on the Utilization of High Strength/High Performance Concrete, May 1996, pp. 711-718.**

In this article, the authors evaluate the applicability of the Freiesleben-Hansen and Pederson maturity function to a high-strength concrete with silica fume and a superplasticizer. "A concrete mixture is allowed to cure under different temperatures in an attempt to cover a wide range of possible field conditions. Different strength-age relationships are studied and a low value of activation energy is estimated. A hyperbolic strength-age relationship is shown to better describe the strength-gain development."

"The ability to correctly predict concrete physical properties at a given time is an important factor in construction. Project schedule is fundamentally linked to concrete strength development. [...] The maturity approach was developed to better estimate the compressive strength in place as a function of the curing temperature."

This study considered five different curing regimes to include cold and hot weather concreting under both isothermal and field conditions. This covered a wide range of possible curing conditions that could be encountered with high-strength concrete.

Three strength-age relationships were discussed in the article: the Freiesleben-Hansen and Pederson exponential equation, the Carino-suggested hyperbolic function, and the Knudsen "parabolic-hyperbolic" equation. The apparent activation energy is calculated for each of these three "models". Different values are given by each of the three strength-age relationships.

"For the high-strength mixture studied, the relationship between compressive strength and maturity was temperature dependent regardless of the model or chosen apparent activation energy value."

The authors found "...that the maturity approach for variable curing conditions is in agreement with results from isothermal curing conditions."

For use in the field, when using the maturity approach to predict compressive strength at early ages, the authors recommend the use of the hyperbolic model as the best predictor of compressive strength.

5.24 **Neville, Adam, SUGGESTIONS OF RESEARCH AREAS LIKELY TO IMPROVE CONCRETE, Concrete International, Vol. 18, No. 5, May 1996, pp. 44-49.**

In this outstanding article, the author suggests 11 different areas of proposed research aimed at improving the use of concrete in practice. Among these 11 areas is moist curing. This suggested research topic is meant to ensure concrete receives adequate moist curing in the field.

In an excellent summary of the major issues surrounding the curing of concrete in general, and certainly applicable to high performance concrete, the author states:

"Curing of concrete has been an integral part of concreting operations for so long that you would not expect it to come under the heading of needed research. I am not referring to the effect of curing on the microstructure of hardened cement paste, but to the methods of ensuring that concrete is cured adequately.

Curing affects primarily the concrete in the cover to reinforcement, and it affects the actual quality of the concrete rather than its potential quality. Moist curing is essential for the cement to hydrate as much as possible; it is worth adding that full hydration is not necessary and, at low water-cement ratios, is impossible.

Curing is invariably specified but it is rarely achieved. Like batching and mixing, curing requires close supervision, perhaps even more so because, in retrospect, it is extremely difficult to prove that proper curing had not been applied. So it is not the specifications that is at issue but the development of means of ensuring good practice."

This article also lists some of the reasons for inadequate curing in the field, as follows:

"First, curing is an operation which follows the end of the concreting operation; in consequence, there is a not-surprising desire to move on to the next phase of work.

Second, curing is seen by many as a silly operation, as a non-job: just sprinkling water, with nothing to show for it at the end of the day. [...]

The third reason for not curing is that most personnel on site, often including even supervisory staff, do not believe in their hearts that curing serves a really useful purpose. [...]

The fourth reason is the rather unkind argument that curing does not show: Who will know tomorrow whether the concrete was subjected to curing today? [...]

The fifth and last reason is the most compelling one, but it is also one that points toward a remedy: curing is not paid for as a separate item. To ensure good curing it would be worthwhile to develop a method of payment for it. This could possibly be by the consumption of ear-marked water, but a more clever method needs to be developed."

The author emphasizes that curing is even more important today than in times past for these reasons:

"First, modern cements, with their higher rate of gain of strength have unwittingly allowed a worsening in the curing practice. The explanation is as follows. Because strengths adequate for the removal of formwork or for trafficking the surface of the concrete are reached very soon, there is an excuse to discontinue effective curing at a very early age.

The second reason is that lower water-cement ratios are used than was the case in the past [such as with high performance concrete] and, to prevent self-desiccation, ingress of water into the concrete is necessary.

Third, modern mixes often contain fly ash and ground granulated blast furnace slag. These materials, especially the latter, react over longer periods of time, and consequently need prolonged curing."

5.25 **Persson, Bertil, HYDRATION AND STRENGTH OF HIGH PERFORMANCE CONCRETE, Advanced Cement Based Materials, Vol. 3, Nos. 3/4, April/May 1996, pp. 107-123.**

"In this article an experimental and numerical study on the hydration, internal relative humidity, and strength of high performance concrete is outlined. For this purpose about 650 cores were drilled out of 24 simulated columns which had a diameter of 1 m (39.4 in.). Eight mixture proportions of concrete were studied. The specimens were air-cured, sealed, or water-cured. Both compressive strength and split tensile strength were studied"

The author considers high performance concrete (HPC) to be a concrete with a 28-day compressive strength exceeding 80 MPa (11,600 psi).

"The main objective of this work was to investigate the long-term strength of HPC subjected to different external conditions, such as air or water, by observing its compressive and tensile strength, hydration, and self-desiccation"

"The long-term development of internal relative humidity, strength, and hydration was studied for eight concretes during sealed curing, air curing, or water curing at 28, 90, and 450 days. The w/c ratio of the concrete varied between 0.22 and 0.58. Half of the concretes contained 10% silica fume."

"The sealed curing exhibited a remarkable self-desiccation, especially when silica fume was utilized in the composition of the concrete. [...] The self-desiccation of concrete was found to be dependent on time and the w/c ratio."

"The strength of the concrete increased continuously during the 450 days independent of the kind of curing. The strength development was also fairly independent of the distance from the cured edge of the rim of the core.... The strength was affected only in concrete of higher w/c ratio by the kind of curing." The author reports "...the strength developed more slowly for concretes containing silica fume than for concretes without silica fume content. Still, the strength of concretes with silica fume increased at least over 450 days."

"The self-desiccation affected the hydration process. For concrete without silica fume, the degree of hydration increased continuously. For concretes with silica fume, however, the degree of hydration decreased after an age of approximately 90 days."

5.26 **Dhir, Ravindra K., Hewlett, Peter C., and Dyer, Thomas D., INFLUENCE OF MICROSTRUCTURE ON THE PHYSICAL PROPERTIES OF SELF-CURING CONCRETE, ACI Materials Journal, Vol. 93, No. 5, September-October 1996, pp. 465-471.**

"During the development of 'self-curing' concrete, it has been found that one particular self-curing admixture used produces a number of effects with respect to particular physical properties and powder x-ray diffraction characteristics. This paper attempts to explain these observations at a microstructural level. Two computer models are used to illustrate the influence the admixture is thought to have on hydrated cement microstructure. At low dosages, good strength and improved permeability characteristics are observed. At high dosages, it appears that the admixture has a detrimental effect on the concrete's compressive strength due to an alteration of the nature of calcium hydroxide at the cement-aggregate interface. However, it seems that at the same dosages the CSH gel structure is altered beneficially, producing a highly impermeable concrete. It is suggested that although a lowering of strength does occur at high dosage, a much lower permeability for a given strength can be obtained."

These same researchers developed a self-curing concrete capable of reduced water loss after placement. "The water retention is induced by the addition of a water-soluble polymeric glycol admixture (polyethylene glycol with an average molecular weight of 200) and leads to an improvement in strength and permeability properties in concrete specimens cured in air due to an increase in the degree of cement hydration achieved."

The major conclusions reported in this paper are:

1. "There is evidence that the chemical [admixture] is altering CSH gel morphology...possibly by growth inhibition. This appears to enhance the nature of the CSH gel, leading to better permeability characteristics.

2. Despite a reduction in strength at high dosages [greater than about 0.02M chemical concentration], it can be concluded that a lower concrete permeability for a given strength can be obtained using this chemical.

The chemical dealt with in this report has the effect of inhibiting growth of calcium hydroxide crystals. The change in CH morphology that results can be detrimental to concrete strengths at high admixture concentrations."

SUBJECT INDEX